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Productive use of energy in women-owned enterprises

A multi-disciplinary approach towards understanding clean energy access in Africa

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Paper	Details	Statement of contributions
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II	Gad, D., Leone, P., Ravetti, C. (under review). Productive use in women-owned enterprises across multiple African countries.	Corresponds to the research presented in Chapter 6

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Summary

This doctoral dissertation investigates the gendered dynamics of productive energy use among micro-, small-, and medium-sized enterprises (MSMEs) across diverse African contexts, with a focus on how clean energy transitions can be effectively designed, financed, and implemented for women-owned businesses. While situated within the broader African energy access agenda, the empirical scope centres on seven selected countries, Egypt, Ghana, Kenya, Malawi, Nigeria, Tanzania, and Tunisia, chosen for their high relevance in terms of productive use in women-owned enterprises. Although global development frameworks, particularly Sustainable Development Goals (SDGs) 5, 7, and 8, prioritise gender equality, sustainable energy, and inclusive economic growth, they offer limited guidance on how to operationalise these goals in enterprise settings shaped by infrastructural gaps, financial exclusion, and gender-related constraints. Women entrepreneurs, in particular, remain peripheral in both energy policy and financing ecosystems, despite their pivotal role in sustaining local economies. This study responds to these gaps by proposing empirically grounded, enterprise-level pathways for inclusive energy transitions.

Using a multi-phased, mixed-methods approach, the research combines literature reviews, secondary data analysis, enterprise surveys, energy audits, and scenario-based techno-economic modelling with environmental impact assessments. It targets two high-relevance sectors, food processing and textiles, where women's entrepreneurship intersects with high and relatively complex energy use. By integrating the World Bank's Multi-Tier Framework (MTF) with HOMER Pro simulations, the research bridges diagnostic assessment with applied system design. A hybrid thematic framework analysis supports the evaluation of viable business models and financing mechanisms. Seven interlinked research questions guide the inquiry, focusing on gendered access patterns, technology adoption, financial architecture, and enabling conditions.

Findings reveal that many women-owned enterprises often remain below MTF tier 3, hindered by unreliable service, affordability barriers, and misaligned technologies. Configurations such as stand-alone solar PV, PV-battery-diesel hybrids, and thermal systems powered by LPG or biomass waste can raise access to tier 4 or 5, but introduce trade-offs in capital cost, complexity, and maintenance. Case studies show that viable business models frequently involve anchor enterprises or cooperative structures, supported by financing strategies like results-

based funding, concessional loans, equipment leasing, or pooled capital, yet gender-responsive finance remains fragmented and underdeveloped.

This exploratory study, while not statistically generalisable, provides rare, empirically grounded insight into enterprise-level energy access realities. It contributes to the scientific and policy discourse by identifying context-sensitive, gender-responsive pathways to accelerate inclusive, clean energy transitions for MSMEs across diverse African settings.

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"When you empower a woman, you empower a nation", a sentiment echoed by many African leaders and changemakers.

I dedicate this work to the women who build, nurture, and transform their communities with resilience, determination, and entrepreneurial spirit, often in the face of structural barriers and unseen struggles. May their lived realities continue to inform and inspire more inclusive energy futures.

List of Abbreviations

ACRE	Access to Clean and Renewable Energy
AD	Anaerobic digestion or anaerobic digester
ADB	Asian Development Bank
AfDB	African Development Bank
ANME	Agence Nationale pour la Maîtrise de l'Énergie
BLDC	Brushless direct current
BLEENS	Biogas, LPG, electricity, ethanol, natural gas, and solar
CAPEX	Capital expenditure
CHP	Combined heat and power
COP	Coefficient of Performance
ECOWAS	Economic Community of West African States
EgyptERA	Egyptian Electric Utility and Consumer Protection Regulatory Agency
ENERGIA	International Network on Gender and Sustainable Energy
EPRA	Kenya's Energy and Petroleum Regulatory Authority
ERI	Electricity Regulatory Index

ESCOM	Electricity Supply Corporation of Malawi
ESCWA	United Nations Economic and Social Commission for Western Asia
ESMAP	Energy Sector Management Assistance Program
EWURA	Tanzania's Energy and Water Utilities Regulatory Authority
FAO	Food and Agriculture Organization of the United Nations
FM	Fresh matter
FTT	Thiaroye Processing Technique
GHG	Greenhouse gas
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
HOMER	Hybrid Optimisation of Multiple Energy Resources
HRT	Hydraulic retention time
IEA	International Energy Agency
IFC	International Finance Corporation
ILO	International Labour Organization
IRENA	International Renewable Energy Agency
KPLC	Kenya Power and Lighting Company
LHV	Lower heating value
MERA	Malawi Energy Regulatory Authority

MSME	Micro-, small-, and medium-sized enterprise
MSW	Municipal Solid Waste
MTF	Multi-Tier Framework
NERC	Nigerian Electricity Regulatory Commission
NGO	Non-Governmental Organisation
NPC	Net present cost
O&M	Operation and Maintenance
PAH	Polycyclic Aromatic Hydrocarbon
PAYGo	Pay-as-you-go
PCAF	Partnership for Carbon Accounting Financials
PURC	Ghana's Public Utilities Regulatory Commission
PV	Photovoltaic
REA	Rural Electrification Agency (applicable to Nigeria) and Rural Energy Agency (applicable to Tanzania)
REF	Rural Electrification Fund (applicable to Nigeria) and Rural Energy Fund (applicable to Tanzania)
SDG	Sustainable Development Goal
SE4ALL	Sustainable Energy for All
STEG	Société Tunisienne de l'Électricité et du Gaz
UNDP	United Nations Development Programme

UNEP	United Nations Environment Programme
UNFCC	United Nations Framework Convention on Climate Change
UN-Habitat	United Nations Human Settlements Programme
USAID	United States Agency for International Development
WEF	World Economic Forum

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Chapter 1

1. Introduction – Why do women-owned enterprises matter for inclusive energy transitions?

1.1 Background and context

As the global momentum toward inclusive energy transitions accelerates, it does so against a backdrop of enduring gender disparities, widespread energy poverty, and entrenched economic exclusion, challenges that are especially acute across sub-Saharan Africa. More than 600 million people in the region still lack access to electricity, and over 900 million rely on traditional biomass for cooking (International Energy Agency (IEA), 2024b; The World Bank Group et al., 2023). For women, especially those running micro-, small-, and medium-sized enterprises (MSMEs), the energy deficit is not merely a matter of infrastructure; it is a constraint on agency, productivity, and socio-economic mobility.

International policy frameworks such as the Sustainable Development Goals (SDGs) articulate a vision for a more equitable and sustainable world. Specifically, SDG 5 (gender equality), SDG 7 (affordable and clean energy), and SDG 8 (decent work and economic growth) offer a shared roadmap toward inclusive development. Yet these goals, while aspirational, often remain disconnected from the practical realities on the ground. They are political constructs rather than operational frameworks, and their broad targets frequently obscure the institutional, financial,

and socio-cultural barriers that shape energy access and usage, especially for women entrepreneurs (Clancy & Dutta, 2005; Dutta et al., 2017; Pueyo & Maestre, 2019).

One of the promising but underexplored pathways to delivering on these global commitments lies in the productive use of energy[1]. Unlike household energy access, which is typically framed around basic needs, productive use focuses on electricity or other energy carriers used for income-generating activities. This includes energy services for machinery, refrigeration, lighting, or heating in production processes (Aarakit et al., 2024). For women-owned MSMEs, access to these services is often patchy, unaffordable, or misaligned with their operational needs (Muza & Thomas, 2022; Patnaik et al., 2021; Pueyo, Carreras, et al., 2020).

This disconnect highlights a deeper structural issue: women-owned enterprises, despite their central role in local economies, are often excluded from energy planning and infrastructure investment. This is not merely a service delivery gap but a form of energy injustice. Overcoming it requires not only expanding renewable energy access but also doing so in ways that account for the gendered, financial, and institutional barriers that constrain productive energy use.

The interplay between renewable energy access, productive use, and gender equity lies at the heart of this thesis. These three dimensions are deeply interconnected: energy systems shape the viability of women-owned enterprises, while institutional exclusions and gendered norms determine who benefits from renewable energy solutions. Figure 1 provides a simplified conceptual overview of this triad, which is further elaborated in Chapter 3. It illustrates how inclusive energy transitions can only be achieved when renewable energy systems are designed to support productive use while addressing gender-specific constraints. This relationship frames the analytical lens of the thesis and underpins the empirical strategy used throughout.

[1] The term “productive use of energy” is interchangeable with the terms “productive use”, “productive energy use”, and “productive activity”.

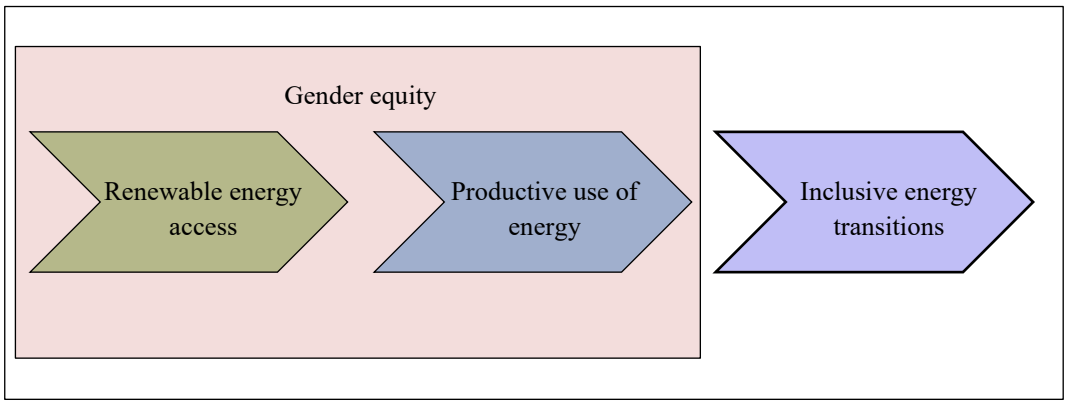

Figure 1. Conceptual overview linking gender equity with renewable energy access and productive use to achieve inclusive energy transitions

1.2 Research problem

While the development literature increasingly acknowledges the importance of gender in energy access debates, most studies stop short of interrogating how women entrepreneurs interact with and are constrained by existing energy systems (Ouziaux et al., 2021; Pueyo, Bawakyillenuo, et al., 2020; Pueyo & Maestre, 2019; Schiffer & Yesutanbul, 2021). Much of the focus remains on household consumption, treating women as domestic users rather than as producers, innovators, and economic agents. This bias is further reinforced by energy access metrics that prioritise electricity over thermal energy and infrastructure over institutional enablers (Clancy & Dutta, 2005; Pueyo et al., 2019; Pueyo & Maestre, 2019).

In sub-Saharan Africa, where women's economic participation is disproportionately concentrated in the informal and small-scale sectors, the invisibility of productive energy use among women-owned enterprises poses a serious empirical and policy challenge (Harvard University & Center for African Studies, 2020; Pueyo, Bawakyillenuo, et al., 2020). First, there is insufficient disaggregated data on women's energy demand beyond the household. Second, few studies assess how financing constraints, ownership structures, and energy system design interact to shape technology adoption. And third, there is limited evidence on the institutional and business models best suited to deliver energy transitions that are not only technically viable but also gender-equitable and financially sustainable (Ferreri et al., 2022; Pueyo, Carreras, et al., 2020).

1.3 Research objectives and questions

This research study addresses these gaps through a multi-phased, mixed-methods research design, assessing the gendered dynamics of productive energy use among MSMEs across seven African countries. It builds a bridge between diagnostic evidence and implementation strategy, grounded in real enterprise scenarios and national contexts. The research is guided by seven interlinked questions:

RQ1: Which African countries and industry sectors offer the most promising empirical grounds for investigating the gendered patterns of productive energy use within MSMEs?

RQ2: To what extent does the gender of the ownership structure influence energy access and productive uses in MSMEs?

RQ3: What are the key characteristics of energy access for productive use among women entrepreneurs?

RQ4: What barriers and drivers influence women entrepreneurs' adoption of renewable energy technologies?

RQ5: How can clean energy technologies be configured to meet the productive energy needs of women-owned enterprises?

RQ6: What techno-economic and environmental trade-offs arise when evaluating energy transition scenarios at the enterprise level?

RQ7: What kinds of business models and financing schemes are most appropriate to support women-owned enterprises under enhanced energy access scenarios in diverse African contexts?

By addressing these questions, the study aims to move beyond high-level advocacy and into the design of implementable, evidence-based strategies that work for enterprises that considerably contribute to Africa's local economies (International Labour Organization (ILO), 2025).

1.4 Methodological roadmap

This thesis adopts a multi-phased, mostly mixed-methods research design to investigate the gendered dynamics of productive energy use among MSMEs across seven African countries. The methodological approach is intentionally multi-disciplinary, drawing from data science, policy analysis, engineering, and socio-economic inquiry to understand how ownership structures, energy technologies, and institutional environments interact to shape women entrepreneurs' energy access and transition pathways.

The research unfolds across sequential and interlinked phases. It begins with secondary data analysis to identify high-relevance countries and sectors, followed by two stages of primary data collection: a web-based survey and face-to-face energy audits. These empirical insights are deepened through energy system modelling, environmental impact assessment, and a framework-based analysis of business models and financing schemes. This sequential logic enables both breadth (comparative, cross-country analysis) and depth (enterprise-level diagnostics).

Table 1 provides a high-level summary of the methodological approach mapped against each of the seven research questions, outlining the corresponding data collection tools, analytical strategies, and expected outputs. Each method is further elaborated in the respective thesis chapters.

Table 1. Overview of the methodological approach and outputs by research question

Research Question	Methodological approach	Main data collection tools	Main analytical tools & indicators	Main outputs
RQ1: Country & industry sector relevance	Mixed-methods secondary analysis	MSME Economic Indicators Database + World Bank Enterprise Surveys + technical reports	MSMEs/1,000 inhabitants; % of women ownership in enterprises; sectoral share of women entrepreneurs	Selected countries & industry sectors

RQ2: Gender-based ownership & energy use	Mixed-methods cross-sectional survey analysis	Web-based survey	Gender-disaggregated descriptive statistics; enterprise-level energy indicators	Energy use patterns by gender-based enterprise ownership
RQ3: Energy access characteristics	Mixed-methods structured energy access assessment	Face-to-face energy audits from 7 countries	World Bank MTF; 8 energy access attributes; tier assignment logic	MTF energy access scores per enterprise
RQ4: Barriers & drivers of renewables adoption	Thematic qualitative analysis	Face-to-face energy audits from 7 countries	Coded interview responses; behavioural intent to invest; preferred finance options	Typology of constraints, motivators, and investment preferences
RQ5: Technology configurations	Techno-economic system modelling	Energy audit-derived load profiles from 6 case studies	HOMER Pro; CAPEX, NPC, O&M costs	Viable energy system configurations for each enterprise
RQ6: Environmental trade-offs	Environmental impact assessment	Energy audit data from 6 case studies + HOMER Pro outputs	GHG Protocol & PCAF	Operational GHG emissions by scenario for each enterprise
RQ7: Business & finance models	Mixed-methods comparative case analysis with framework synthesis	Data from 6 case studies + scientific and grey literature	Enabling environment matrix; deductive-inductive logic	Business model-finance-context fit profiles

Abbreviations: CAPEX = capital expenditure; GHG = greenhouse gas; HOMER Pro = Hybrid Optimization of Multiple Energy Resources Professional; MTF = Multi-Tier Framework; MSME = micro-, small-, and medium-sized enterprise; NPC = net present cost; O&M = Operation and Maintenance; PCAF = Partnership for Carbon Accounting Financials; RQ = research question

This structured, multi-method roadmap ensures that each research question is addressed with an appropriate mix of tools and perspectives, combining quantitative and qualitative evidence across technical, economic, and institutional dimensions.

1.5 Significance and contribution

While this research does not aim to produce statistically representative results or infer causal relationships, it offers empirically grounded insights drawn from a limited yet rich dataset. The methodological approach is exploratory rather than generalisable, and findings should not be uncritically extended to other contexts. The relatively small sample size, particularly in the qualitative strand, is an intentional design choice to prioritise depth over breadth. The aim is to generate transferable insight rather than generalisable claims, in line with recent best practices in gender-energy research in under-researched contexts. However, within these bounds, the study makes four key contributions to the academic and policy discourse at the intersection of energy access, productive use, and gender analysis.

First, it repositions women entrepreneurs as productive energy users, not merely as household consumers. It disaggregates their needs across energy types, ownership structures, and sectors, offering an enterprise-level analysis still rare in the literature (Asibey et al., 2021; Pueyo & Maestre, 2019).

Second, it brings methodological innovation to gender-energy research. The application of the World Bank's Multi-Tier Framework (MTF) to enterprise-level energy access provides a multidimensional assessment, while the modelling of clean energy scenarios with the Hybrid Optimisation of Multiple Energy Resources Professional (HOMER Pro) tool adds technical and financial rigour.

Third, the research bridges technological design and financing architecture. By assessing real-world enterprise case studies in Ghana, Tunisia, Kenya, Malawi, Nigeria, and Tanzania, the study not only evaluates system performance (e.g. reliability, cost, emissions) but embeds these insights in national policy frameworks and gendered financial realities.

Fourth, the thesis proposes a practical business and financing model, including community-anchored services, cooperative governance, lease-to-own systems, and blended capital structures, that reflects enterprise capacities and risks. These models are not prescriptive blueprints but adaptive configurations that can be replicated or refined.

Collectively, these contributions advance the scientific understanding of how gender-responsive energy access can be achieved, not as a downstream benefit but as a central design principle of inclusive and sustainable development.

1.6 Thesis structure

The thesis is organised into nine chapters, following a coherent analytical arc from conceptual framing to empirical exploration, modelling, and policy implication. Each chapter follows a consistent structure comprising an introduction, materials and methods, results, discussion, and conclusion.

Chapter 1 introduces the research, framing the study within development debates and outlining its research design. **Chapter 2** sets out the ethical foundations of the study, addressing the methodological challenges of conducting gendered energy research across diverse African contexts. **Chapter 3** develops an analytical framework through an integrated literature review, establishing conceptual clarity on gender, productive energy use, and access indicators. **Chapter 4** identifies the empirical focus areas through secondary data analysis, selecting countries and sectors that best reflect the research problem. **Chapter 5** presents a web-based survey that investigates how gender ownership structures shape energy access and productive energy use across MSMEs. **Chapter 6** draws on face-to-face interviews and MTF assessments to map energy service levels, technology adoption barriers, and investment preferences among women entrepreneurs. **Chapter 7** models enhanced energy access scenarios across six enterprise case studies, analysing techno-economic and environmental trade-offs under different configurations. **Chapter 8** evaluates viable business models and financing mechanisms to support the clean energy transitions identified in Chapter 7, linking them to broader policy and regulatory environments. **Chapter 9** synthesises the findings, discusses their implications for inclusive energy and enterprise development, and outlines a forward-looking agenda for research and practice.

Through this structure, the thesis contributes both theoretically and practically to a deeper, more actionable understanding of how energy systems can be reimagined to better serve women entrepreneurs, unlocking their productivity, resilience, and developmental potential in Africa's rapidly transforming energy landscape.

Chapter 2

2. Ethical considerations and data collection strategies – What are the ethical imperatives in gender-energy research?

2.1 Introduction

In research addressing gendered dimensions of energy access, as in any research involving research participants, ethical considerations must be central, not only as procedural obligations but as commitments to equity, respect, and scientific responsibility (Orb et al., 2001; Regmi et al., 2016). This study adopts a mixed-methods approach, integrating quantitative assessments with rich qualitative inquiry. While the quantitative component offers breadth, the qualitative dimension plays a critical role in contextualising energy access patterns, deepening insights into lived experiences, and interpreting the nuanced realities of women entrepreneurs.

Conducting this research across seven African countries, engaging with diverse cultural contexts and varying levels of institutional infrastructure, demanded a thoughtful, ethically anchored approach. This chapter describes the ethical frameworks and practical procedures guiding data collection, as well as the dilemmas encountered and mitigated throughout the fieldwork process. These ethical reflections are situated within well-established research principles: autonomy, beneficence, and justice (Orb et al., 2001). These principles help negotiate the inherent tension between advancing generalisable knowledge and protecting the rights of the individual participants.

2.2 Materials and methods

This study did not seek formal clearance from an ethics committee, as the research posed minimal risk to participants, adhered strictly to anonymisation protocols and operated on the principle of voluntary participation (Orb et al., 2001; Regmi et al., 2016). Informed verbal consent was obtained from all participants prior to data collection. This process was facilitated through trusted third-party intermediaries, such as governmental bodies, regional industry associations, and development agencies, who introduced the study, brokered trust, and helped identify eligible enterprises while highlighting the principles of voluntary participation, data protection, and confidentiality.

The research drew on a two-fold data collection strategy: a structured web-based survey and semi-structured face-to-face interviews. Both methods were designed and implemented in alignment with ethical guidelines emphasising informed participation, confidentiality, and ongoing consent.

The web-based survey, developed in Google Docs, followed scientific standards in digital research design (Andrews et al., 2003; Regmi et al., 2016). Questions included both closed- and open-ended formats, offering participants flexibility in how they shared information. The survey platform supported cross-browser compatibility and was optimised for low-bandwidth regions. Sensitive questions were accompanied by "prefer not to say" options. To uphold participant anonymity, no personally identifiable information, such as names, email addresses, or IP data, was collected. As such, individual responses could not be traced back to participants. Despite these efforts, it is widely acknowledged that web-based surveys often yield low response rates, particularly among underrepresented or digitally marginalised groups (Andrews et al., 2003), a challenge also observed in this study.

To address the limitations of remote data collection and better understand energy use dynamics in small enterprises, more detailed energy audits in the form of in-person interviews were conducted. These interviews were guided by the Interview Protocol Refinement Framework (Castillo-Montoya, 2016), which provides a structured yet adaptable approach to crafting purposeful and respectful qualitative inquiry. The interview protocol included introductory scripts, aligned questions with research objectives, and incorporated expert feedback during development. Due to time and logistical constraints, the fourth phase of piloting the protocol was not executed.

Interviews took place in-person, with participants selected based on their engagement with the survey and geographic accessibility. Sessions lasted approximately 60 minutes and were guided by an open-ended questionnaire designed to elicit both descriptive and reflective responses. Where consent was granted, interviews were audio-recorded. If participants expressed discomfort or privacy concerns, interviews proceeded without recording and were documented manually using a structured paper-based form. Participants were also explicitly informed of their right to decline to answer any question or skip sections at any point, without the need to provide a justification. This flexible approach supported ethical responsiveness and prioritised participant comfort.

2.3 Results

Data collection revealed significant variation in participation across the two methodological strands. Approximately 200 individuals were directly contacted through an intensive, year-long outreach campaign, forming a central database from which participants for both the web-based survey and face-to-face energy audits were recruited.

For the web-based survey, only 65 valid responses were included in the final analysis. This figure excludes additional responses potentially generated via links shared independently by third-party organisations, making it difficult to estimate total reach or calculate an accurate response rate. This outcome reflects a well-documented challenge in digital data collection: low participation rates are common, particularly among marginalised populations with limited access to digital technologies and when dealing with complex or technical subject matter (Andrews et al., 2003). Although trust was partially established through collaboration with local intermediaries, participation barriers remained. These were mitigated to some extent by thoroughly briefing third-party partners on the research objectives and ethical standards.

For the energy audits, a total of 40 face-to-face interviews were successfully conducted across the seven study countries. Interviewees were drawn from the same database, selected based on their willingness, accessibility, and relevance to the study's objectives. Throughout the interview process, participants were reminded of their rights, including the right to skip questions or terminate the interview at any point. No major ethical incidents occurred. Minor logistical or scheduling challenges were addressed promptly, and in instances where participants expressed discomfort with audio recording, interviews were documented using structured,

paper-based forms, ensuring that participant autonomy and comfort were prioritised.

To summarise the ethical safeguards adopted across the two data collection strands, Table 2 presents the specific standards, practices, and procedural activities undertaken, reflecting how core ethical principles, such as autonomy, beneficence, justice, and confidentiality, were operationalised.

Table 2. Ethical safeguards operationalised across the web-based survey and face-to-face interviews

Ethical principle	Web-based survey procedures	Face-to-face interview procedures
Informed consent	Verbal informed consent via trusted intermediaries; participants explicitly informed of voluntary participation and right to withdraw or skip questions	Explicit verbal informed consent obtained at interview initiation; continuous consent process with rights reiterated throughout the interview
Privacy & confidentiality	Secure digital storage; anonymised responses; sensitive questions included "prefer not to say" options	Personal identifiers avoided; structured paper-based documentation anonymised; audio recording only with explicit consent
Participant autonomy	Participants were provided with flexibility to save progress and return later; explicit options were provided for skipping questions without justification required	Participants were explicitly informed of their rights to skip questions, terminate interviews, or decline recording at any time without justification
Justice & accessibility	Survey platform optimised for low bandwidth and multiple devices; support via intermediaries provided for participants with limited digital access or literacy	Interviews arranged according to geographic accessibility, inclusive selection of rural and marginalised participants; snowball sampling applied to

		reach beyond the initial database
Beneficence & ethical incidents	Minimal ethical incidents; monitoring of participant comfort levels through intermediaries	No major ethical incidents; minor logistical or scheduling adjustments swiftly resolved; participant discomfort regarding audio recording addressed immediately by switching to manual documentation

2.4 Discussion

This chapter illustrates the importance of embedding ethical principles not only in research design, but in ongoing engagement with participants, especially a multi-country, mixed-method study. The intersection of qualitative and quantitative approaches necessitated diverse ethical strategies tailored to the mode of interaction, level of participant vulnerability, and logistical constraints.

The web-based survey, while efficient and scalable, encountered limitations familiar in digital research, especially with hard-to-reach populations: digital exclusion, trust gaps, and privacy apprehensions (Andrews et al., 2003). In response to these known challenges, and in line with recommendations from the literature, the research employed a hybrid recruitment strategy, inviting participants via email while also leveraging offline outreach channels through trusted local intermediaries. This approach follows Andrews et al. (2003) suggestion that email, when complemented by offline communication, can serve as a robust vehicle for engaging participants in web-based surveys. Ethical safeguards were embedded throughout the process: participants were fully informed of their rights, assured of data protection, and reminded that participation was voluntary, with no obligation to answer all questions.

However, it is important to acknowledge an inherent selection bias, particularly in the web-based strand: only individuals with some degree of technological access, internet connectivity, and the ability to understand and respond in English or French were eligible. This limitation was partially mitigated by allowing trusted intermediaries to assist participants in completing the survey where feasible, thus broadening access within the digital constraints. Moreover, the face-to-face interviews, though initially recruited from the same database pool, also employed a

snowball sampling approach, enabling access to even more marginal participants who may have otherwise remained off the radar of development organisations, government agencies, or industry associations.

In contrast to the web-based survey, the face-to-face interviews facilitated deeper relational engagement. Yet they posed their own ethical challenges, including managing interpersonal dynamics and respecting boundaries in culturally diverse settings. The approach taken, prioritising consent, adapting to local preferences, and maintaining flexibility, aligns with the ethical stance that research must be a negotiated, participant-centred process (Orb et al., 2001). The use of recording was treated with caution, used only with consent, and deliberately excluded when concerns arose, an important recognition of both privacy and power imbalances.

The research also revealed gaps: the absence of a formal clearance from an ethics committee may limit broader validation and trust among participants, while the omission of piloting the interview protocol constrained methodological refinement. Nevertheless, the strong ethical grounding applied in practice ensured that participants were respected, protected, and meaningfully engaged.

2.5 Conclusions

This chapter affirms that ethical integrity in mixed-methods gender-energy research is neither static nor procedural; it is dynamic, context-specific, and shaped through constant reflection. The research navigated multiple dimensions of ethical engagement: informed consent, respect for autonomy, avoidance of harm, and commitment to justice. The integration of quantitative and qualitative strands required not only methodological diversity but ethical versatility. While response rates remained a challenge, especially online, the strategies deployed, such as verbal consent, trusted intermediaries, and participant-driven interview processes, provided effective ethical safeguards.

Future research in this space could consider clearance from an ethics committee where feasible, pilot instruments rigorously, and expand digital inclusion strategies. In sum, ethics was not simply a box to check but a lens through which interactions, decisions, and interpretations were viewed.

Chapter 3

3. Understanding gendered energy dynamics – What is the current knowledge on the gender-energy-nexus and which gaps exist?

3.1 Introduction

The intersection between energy access, productive use, and gender is increasingly recognised as a critical dimension in the pursuit of sustainable development. Yet, despite notable progress in energy and development research over the past decades, the gender-energy nexus remains insufficiently explored, particularly when moving beyond household-level analyses to enterprise and income-generation dimensions (Fridriksson et al., 2019; Ingole, 2024; Ngoo & Kooijman, 2020; Ouziaux et al., 2021; Pueyo & Maestre, 2019; Schiffer & Yesutanbul, 2021). Global development efforts in this research field are often framed around the internationally recognised Sustainable Development Goals (SDGs), particularly SDG 5 (gender equality), SDG 7 (affordable and clean energy), and SDG 8 (decent work and economic growth). While the SDGs represent important political commitments acknowledged by the international community, they are not scientific constructs per se but rather serve as normative frameworks aiming to guide policy and action. Within this broader political agenda, a deeper, scientifically grounded understanding of the differentiated experiences, barriers, and opportunities faced by women entrepreneurs in accessing and utilising energy services remains essential (Clancy & Dutta, 2005; Pueyo, Bawakyillenuo, et al., 2020; Pueyo, Carreras, et al., 2020).

This chapter develops an integrated analytical framework that moves beyond fragmented conceptualisations. Rather than treating energy access, productive use, and gender analysis as isolated spheres, it weaves these domains into a coherent

narrative. The chapter first establishes conceptual and terminological clarity: outlining the role of renewable energy in advancing sustainable energy access, tracing the definitional evolution and sectoral breadth of productive uses of energy, and highlighting the critical importance of gender analysis, grounded in frameworks such as the SAGER guidelines (Heidari et al., 2016; Van Epps et al., 2022). Particular attention is paid to the African context, where renewable energy expansion and gender equity are increasingly viewed as interdependent pillars of inclusive growth.

Following this conceptual grounding, the chapter undertakes a quasi-systematic, qualitative literature review to map the current state of empirical research on gendered productive uses of energy, with a focus on women entrepreneurs across Africa, where disparities in energy access, affordability, and productive application remain especially pronounced (Asibey et al., 2021; Pueyo, Carreras, et al., 2020; Pueyo & Maestre, 2019). The literature review draws systematically from both peer-reviewed academic research and reputable grey literature, capturing a comprehensive spectrum of evidence across different geographical and thematic contexts. The review strategy is designed to progressively sharpen its analytical lens: beginning with the gendered challenges of household energy access, advancing through the differentiated impacts of electrification beyond the domestic sphere, and moving toward the emerging role of women as active agents in renewable energy deployment. It then delves into the gendered patterns of productive energy use within enterprises, culminating in a focused analysis of women entrepreneurs as critical, but underserved, energy end-users. Finally, attention turns to persistent gender gaps within the energy sector workforce. In doing so, the chapter traces a deliberate trajectory from access constraints to agency, productive use, and structural participation, offering both context sensitivity and conceptual precision.

By building a robust conceptual and empirical foundation, the chapter positions the subsequent analysis to contribute meaningfully to debates on energy justice, inclusive economic growth, and sustainable development.

3.2 Materials and methods

The objective of the quasi-systematic literature review was to systematically identify, extract, and critically analyse relevant peer-reviewed and grey literature to build a robust interdisciplinary evidence base. The review strategy prioritised

methodological transparency, thematic breadth, and critical depth, ensuring that both conceptual frameworks and empirical trends were rigorously captured.

The conceptual frameworks informing this chapter on renewable energy's role in sustainable energy access, evolving definitions of productive use of energy, and the analytical concept of gender are drawn from contemporary scientific debates. While these frameworks are established through secondary literature engagement, they are not products of a formal systematic search protocol. Instead, they reflect a synthesis of leading academic contributions and recent empirical advances, including but not limited to studies by Aarakit et al. (2024, Heidari et al. (2016), Ingole (2024), Kapadia (2004), Muza & Thomas (2024), Pueyo & Maestre (2019), Raji et al. (2024).

In contrast, the literature review followed a quasi-systematic protocol. The review began with a structured database search using Scopus, which was selected over Web of Science due to its broader coverage of interdisciplinary materials, particularly in the relatively young field of gender and productive energy use (Asibey et al., 2021). While Web of Science is known for offering a deeper historical archive, Scopus was deemed more suitable for this research, given its inclusion of more recent publications spanning technical, social science, and humanities domains. The search protocol employed Boolean operators and wildcard symbols to refine results, targeting documents where variations of the terms "energy", "productive use", and "gender" appeared in titles, abstracts, or keywords. An English language restriction was applied, which yielded an initial pool of 28 peer-reviewed sources, encompassing journal articles, book chapters, conference proceedings, and review papers.

To ensure the inclusion of practical, policy-relevant insights beyond academia, this study drew on a diverse range of grey literature sources. These include reports, working papers, technical briefs, and guidelines produced by international development banks such as the World Bank Group and the Asian Development Bank (ADB), multilateral and intergovernmental agencies including various United Nations bodies and the International Renewable Energy Agency (IRENA), non-profit and advocacy organisations such as Practical Action, ENERGIA (the International Network on Gender and Sustainable Energy), and the RES4Africa Foundation, and sectoral industry associations like the Africa Solar Industry Association (AFSIA). Grey literature documents were selected based on their focus on productive energy use, gender, or both, applying inclusion criteria parallel to

those used for peer-reviewed sources. This expanded the document corpus by 69 additional publications.

A rigorous selection and coding process followed. Each document, whether peer-reviewed or grey literature, was manually reviewed and coded according to key attributes, including title, document type, publication year, institutional affiliation (where relevant), geographic focus, methodological approach, thematic relevance, and key findings. Particular attention was paid to how gender dimensions were addressed in relation to energy use, whether directly through targeted interventions or indirectly through broader development strategies. This coding facilitated structured thematic synthesis while preserving the nuance of individual studies and reports.

During the initial sourcing phase, a total of 97 documents were identified. An initial round of screening, based primarily on keyword matches and general relevance to the research scope, reduced this pool to 76 documents, comprising 18 peer-reviewed journal articles and 58 grey literature publications. However, at this stage, some sources remained that were only tangentially related or lacked thematic alignment. A second, more targeted review of abstracts was therefore undertaken to assess each source's substantive contribution. This led to a refined selection of 61 documents, 11 peer-reviewed articles and 50 grey literature sources, that offered clear thematic relevance and analytical value across the defined focus areas of the review. As shown in Figure 2, this stepwise filtering process was necessary to ensure that only the most pertinent, high-quality sources were included in the final synthesis.

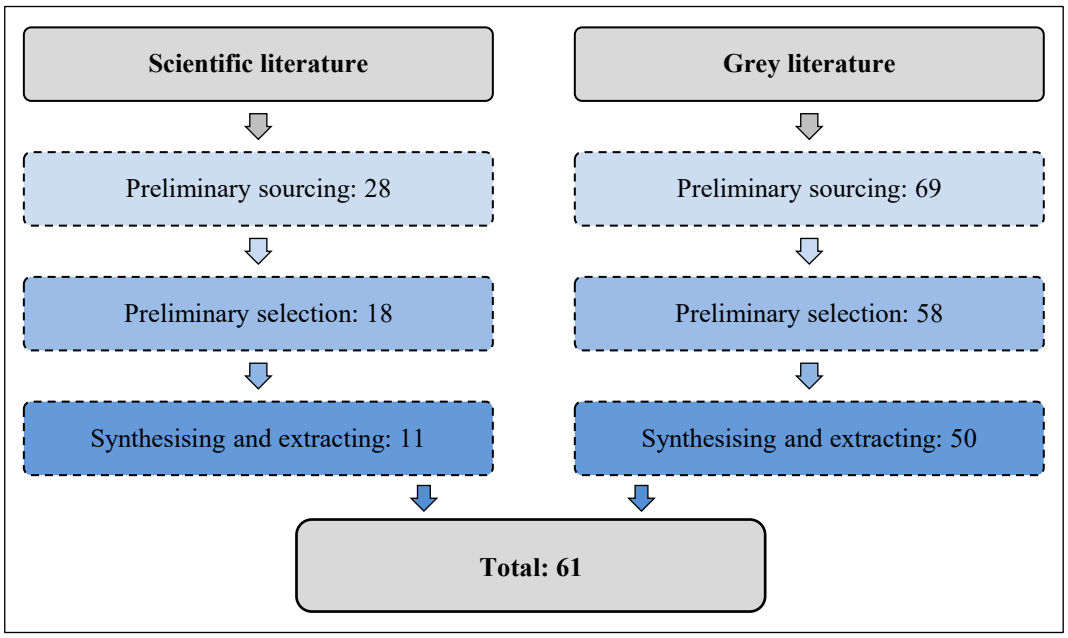

Figure 2. Number of publications from preliminary sourcing and selection to synthesising and extracting

The publication trend observed across the selected documents offers important context. The significant number of publications identified in grey literature indicates a notable interest in the discussion surrounding gender-specific productive energy use on the global stage. Scholarly attention to gender-specific productive use of energy has significantly increased over the past decade, particularly following the adoption of the SDGs in 2015, which has catalysed research interest and international funding for gender and energy topics. The majority of peer-reviewed articles included in the review were published in 2020 and 2023, while grey literature outputs peaked notably in 2020, with a total of 11 publications that year. As illustrated in Figure 3, while the research topic has been gaining some traction, it remains relatively underrepresented in both scientific and grey literature. Overall publication output peaked in 2020 with a total of 14 publications. The years 2019, 2021, and 2022 also recorded relatively higher activity with eight to nine publications per year. In contrast, publication output in all other years between 2004 and 2025 remained significantly lower.

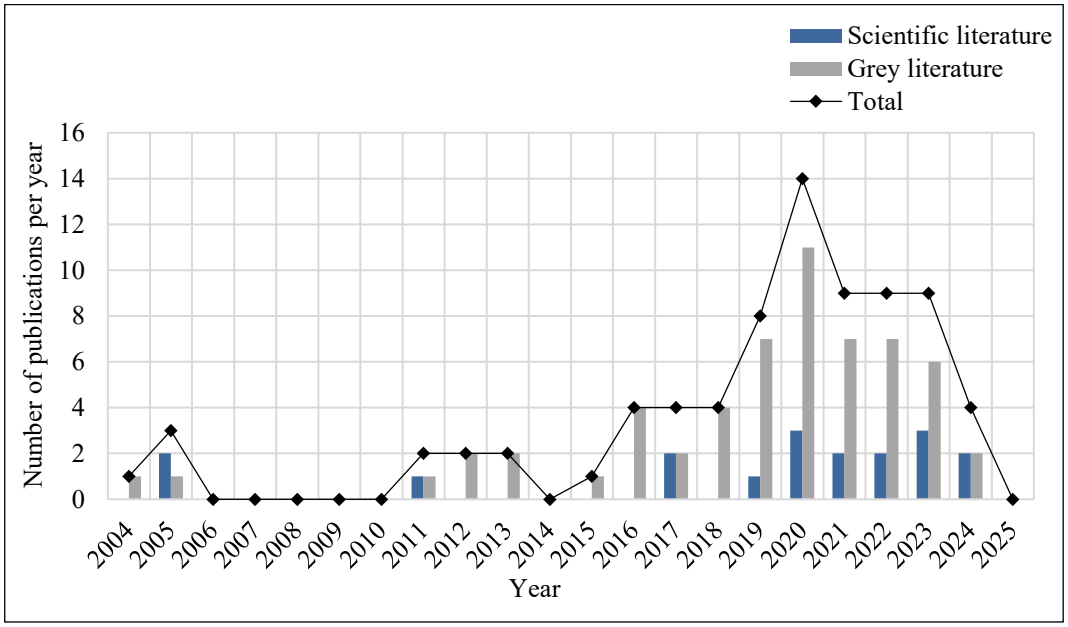

Figure 3. Number of publications from the preliminary selection phase, covering gender-specific productive use of energy, by year and type of literature

Geographically, the focus of publications aligns with regions where access to productive energy use is a prominent issue, namely in Africa, Asia, and Latin America. Both peer-reviewed and grey literature heavily feature countries such as Ghana, Kenya, Nigeria, Rwanda, South Africa, and Tanzania, with scientific publications also covering Ethiopia and Uganda, and grey literature extending to Morocco and Senegal.

Overall, the quasi-systematic review methodology ensures that the subsequent analysis rests on a comprehensive and interdisciplinary evidence base. By synthesising both scientific and practitioner perspectives, and by progressively narrowing from broad thematic concerns to specific attention to women entrepreneurs as energy end-users, the literature review provides a robust foundation for the results and discussions that follow.

3.3 Results

The empirical analysis in this chapter is grounded in a conceptual framework that recognises the deep interconnections between energy access, productive use, and gender dynamics in the context of sustainable development. Rather than presenting isolated theoretical concepts, the following section weaves these

dimensions together to establish an integrated analytical lens. The narrative progresses logically: from the significance of renewable energy for sustainable energy access, through the critical role of productive energy use, to the necessity of embedding a gender-responsive perspective. Only after laying this conceptual foundation does the chapter transition into a quasi-systematic literature review that maps the existing evidence on gender-specific dynamics in productive energy use, with particular attention to women entrepreneurs in sub-Saharan Africa.

3.3.1 Conceptual and terminological frameworks

Energy access through renewable energy is widely considered a cornerstone for achieving sustainable development, particularly in low-income regions characterised by energy poverty and underdeveloped infrastructure (Foster, 2024; Ingole, 2024; Shastry & Rai, 2025). In the African context, where dependence on traditional biomass remains high and electrification rates are among the lowest globally (The World Bank Group et al., 2023), the transition to renewable energy is increasingly framed not just as a climate imperative but as an essential lever for poverty alleviation, inclusive economic growth, and social justice (Foster, 2024; Işık, Bulut, et al., 2024; Işık et al., 2023). However, as research grounded in the Environmental Kuznets Curve (EKC) hypothesis[2] indicates, the relationship between economic growth, environmental quality, and energy transition is neither linear nor automatic (Işık, Ongan, & Islam, 2024; Işık, Ongan, Islam, et al., 2024). While renewable energy adoption is often associated with reduced environmental degradation in middle-income contexts, outcomes remain highly context-dependent, influenced by institutional capacity, governance quality, and socio-economic inequality (Pollitzer & Lee, 2020).

Crucially, there is growing consensus that expanding renewable energy access must be coupled with interventions that stimulate productive uses of energy to realise meaningful development impacts (Dagnachew et al., 2023; Foster, 2024; Schöne et al., 2024). Mere access to energy is insufficient if it remains underutilised. Reflecting this recognition, the concept of productive use of energy has evolved considerably in both academic and policy discussions, reflecting its increasing centrality to debates on sustainable development, energy access, and socio-economic transformation. Yet no singular definition of productive use has

[2] For more detailed information on the Environmental Kuznets Curve (EKC) hypothesis, kindly refer to the specified sources indicated by (Işık, Bulut, et al., 2024; Işık et al., 2023), as elaborating further on this topic would extend beyond the scope of this research.

gained universal acceptance, and existing conceptualisations span multiple dimensions (Aarakit et al., 2024).

Some definitions focus narrowly on the form and medium of energy, distinguishing between electric and non-electric energy carriers and the end forms in which energy is utilised, such as heat, mechanical power, or electricity (Aarakit et al., 2024; Cabraal et al., 2005). Others adopt broader perspectives, conceptualising productive use primarily in relation to the activities it enables, notably in agriculture, manufacturing, commerce, and services (Kapadia, 2004; Muza & Thomas, 2022). These broader framings emphasise not merely energy as a resource, but energy as a catalyst for improving livelihoods, creating jobs, and enabling welfare-enhancing services such as health care, education, and improved gender equity outcomes (Aarakit et al., 2024; Muza & Thomas, 2022). Building further on these activity-based conceptualisations, recent research has classified productive uses of energy across primary, secondary, and tertiary sectors (Muza & Thomas, 2024). In the primary sector, energy supports activities centred around natural resource extraction and agriculture, including solar-powered irrigation, livestock and poultry farming, aquaculture, and food conservation. The secondary sector encompasses small-scale industrial activities such as shoemaking, welding, baking, and carpentry, where energy access enables greater mechanisation and productivity gains. In the tertiary sector, productive uses extend to service-based enterprises such as gastronomy, beauty salons, printing, and hospitality. Recognising these sectoral differentiations is crucial for designing targeted energy interventions that are sensitive to local economic structures and capable of maximising developmental outcomes.

Beyond sectoral categorisations, productive use is also frequently framed along three functional dimensions: first, improving the productivity of existing income-generating activities; second, enabling the uptake and utilisation of new energy-powered technologies, often through decentralised renewable energy systems; and third, fostering the creation of new enterprises and employment opportunities following electrification (Aarakit et al., 2024). Importantly, while the provision of energy infrastructure is a necessary precondition, scholars caution that energy alone does not guarantee productive outcomes. Factors such as financial access, technical skills, market linkages, human capital, infrastructure quality, and institutional support all mediate the success of productive energy initiatives (Aarakit et al., 2024; Ingole, 2024; Raji et al., 2024).

While the definitional debates provide a necessary foundation, empirical research underscores the importance of context-specific, multi-dimensional interventions. Raji et al. (2024), through a systematic review of the electricity-agriculture nexus in sub-Saharan Africa, show that productive use cases are dominated by primary sector activities like irrigation. However, they identify persistent constraints including unreliable power supply, limited technical expertise, inadequate financial services, and underdeveloped market structures that inhibit broader impacts. Farthing et al. (2023) and Foster (2024) further demonstrate that integrating productive applications such as solar milling, refrigeration, water pumping, and cold storage into rural renewable energy systems can significantly boost agricultural output, employment, and resilience, although technical feasibility alone is not sufficient for success.

Ingole (2024) provides robust evidence from a quasi-experimental study in India showing that solar energy interventions led to significant income gains and social improvements, but only where policy frameworks facilitated concessional finance and local supply chains were strengthened. Shastry & Rai (2025) deepen this understanding by proposing an "impact-resilience" framework, demonstrating that decentralised renewable energy-assisted machines (DREAMs) not only improve financial outcomes but also catalyse broader livelihood resilience.

Stimulating productive demand is increasingly recognised as vital for the financial sustainability of rural electrification. Lukuyu & Taneja (2023) argue that without appliance financing, tariff reforms, and structured strategies to encourage energy-intensive activities, many electrification projects risk financial failure. Dagnachew et al. (2023) reinforce this view, projecting that productive use activities can raise household electricity demand by approximately 50%, reshaping the cost dynamics of rural energy systems. However, enabling this productive demand requires more than simply providing electricity connections; it demands integrated support systems that address barriers to entrepreneurship, financing, technology adoption, and market access.

Still, productive uses of energy are not uniformly distributed across social groups. A growing body of research critiques the implicit gender neutrality assumed in many productive use programmes (Clancy & Dutta, 2005; Pueyo et al., 2019). Studies show that male-owned enterprises tend to occupy more energy-intensive sectors (e.g., agri-processing, welding, fishing), whereas women entrepreneurs are often concentrated in less energy-intensive, lower profit-margin activities (e.g., food vending, tailoring) (Asibey et al., 2021; Pueyo, Carreras, et al., 2020; Pueyo

et al., 2019). Moreover, women face compounded barriers, lower access to finance, reduced control over land and assets, and social norms restricting participation in technical sectors (Clancy & Dutta, 2005; Pueyo, Bawakyillenuo, et al., 2020; Pueyo, Carreras, et al., 2020).

Understanding these patterns necessitates clear conceptual differentiation between sex and gender. Following the SAGER guidelines (Heidari et al., 2016; Van Epps et al., 2022), "sex" refers to biological characteristics related to physical and physiological traits, such as chromosomes, hormone function, gene expression, and reproductive anatomy, typically classified as female or male. In contrast, "gender" encompasses socially constructed roles, behaviours, identities, and power dynamics that shape individual and collective experiences beyond biological differences. Gender influences how power and resources are distributed within societies, often reinforcing inequalities across economic, social, and political domains.

In the context of energy access research, it is primarily gender, not sex, that determines disparities in service provision, technology adoption, and the realisation of productive benefits. Therefore, while collecting sex-disaggregated data (separating information into female/male categories) remains necessary, it is not sufficient on its own. Gender-disaggregated analysis is crucial for revealing how social norms, institutional biases, and power relations affect energy outcomes (Ferroukhi, Renner, et al., 2019). Recognising this distinction ensures that research captures not only binary differences but also the broader and more complex ways in which energy systems intersect with societal structures of inclusion and exclusion.

Thus, the frameworks established in this section jointly argue that renewable energy deployment, productive energy use strategies, and gender mainstreaming must be analytically and practically intertwined. Figure 4 illustrates the conceptual framework underpinning this study, highlighting the interlinked roles of energy access through renewable energy deployment, productive use of energy, and gender mainstreaming in achieving inclusive, sustainable energy transitions pathways.

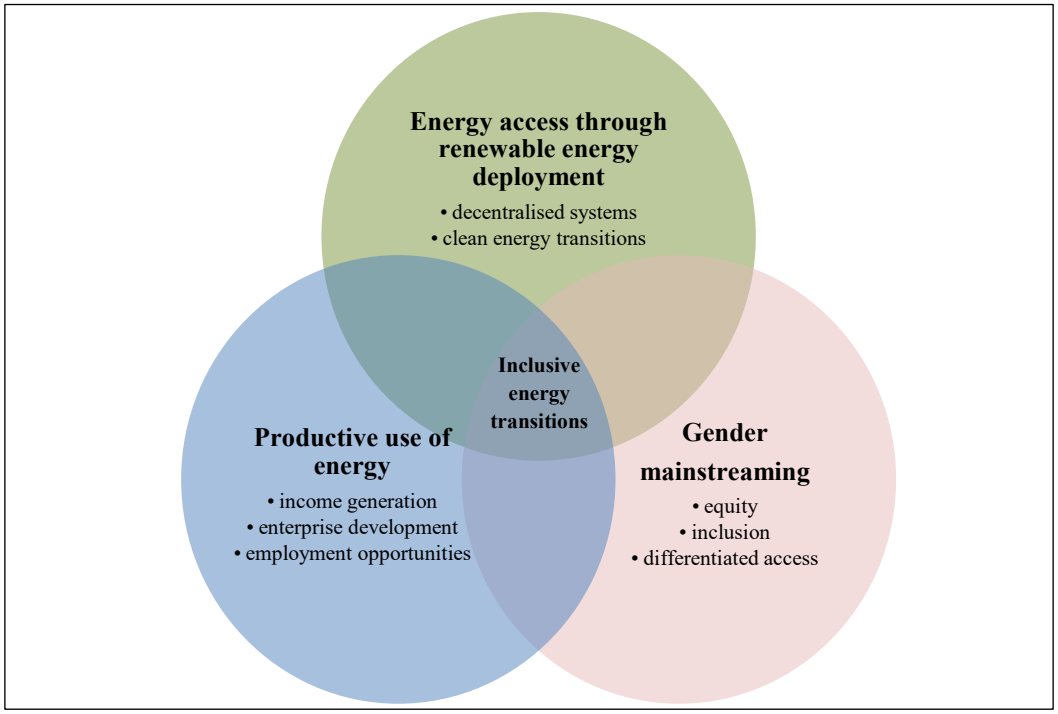

Figure 4. Conceptual framework connecting energy access through renewable energy deployment, productive use of energy, and gender mainstreaming

This research contends that without explicitly integrating the interconnected dimensions of sustainable energy access, productive use, and gender mainstreaming, energy interventions risk entrenching, rather than alleviating, the structural inequities that perpetuate energy poverty. Recognising these interdependencies is essential for designing transformative rather than merely technical solutions. These foundational insights set the stage for the subsequent quasi-systematic literature review, which critically examines how contemporary research engages with the intersections between gender-responsive energy access strategies, productive energy use, and women's entrepreneurship.

3.3.2 Current research status: Literature review findings

The following section presents the results of the quasi-systematic literature review, systematically organised into thematic blocs to synthesise the current state of knowledge at the intersection of energy access, productive energy use, and gender analyses. Rather than treating gender as a peripheral variable, the review

highlights how deeply embedded gendered dynamics are within energy systems, influencing access, utilisation, and benefit distribution. Drawing on an extensive body of peer-reviewed academic research and reputable grey literature, the synthesis follows a logical progression: beginning with the gendered dimensions of basic household energy access challenges, advancing to the differentiated impacts of electrification beyond the domestic sphere, and subsequently examining women's roles as agents driving renewable energy access. It then explores gendered patterns of productive energy use in enterprises, before culminating in an analysis of women entrepreneurs as critical but underserved energy end-users. Finally, attention turns to the persistent gender gaps in workforce participation within the broader energy sector.

This sequencing, moving from access constraints to agency, productive use, and structural participation, not only organises the available empirical evidence but also reveals persistent blind spots, entrenched barriers, and emerging opportunities for more gender-responsive energy interventions. Figure 5 provides an overview of the thematic blocs employed to structure the literature review and guide the analytical synthesis that follows.

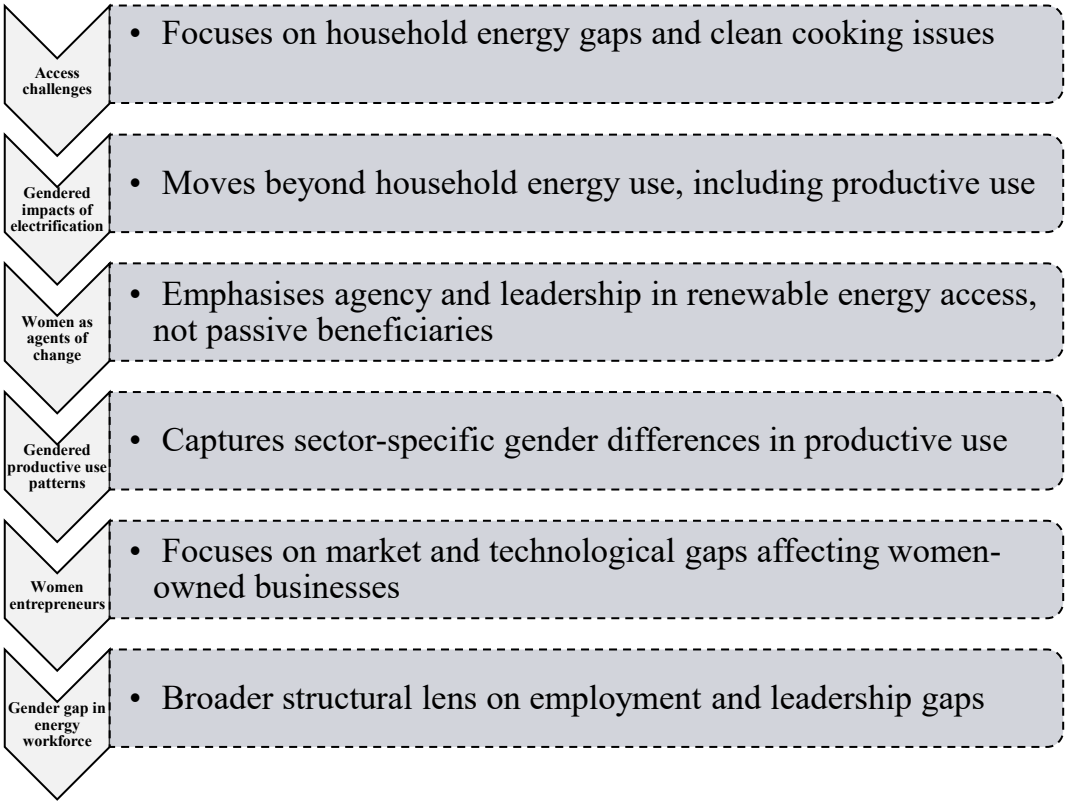

Figure 5. Thematic structure of the literature review

3.3.2.1 Energy access challenges and energy needs

Recognising the intersection of gender and energy needs is not new: attention to the women-energy nexus dates back to the late 1970s, with early research highlighting women's burdens in gathering fuelwood for cooking (Asibey et al., 2021). Despite these early insights, much of the subsequent research and policy-making continued to frame energy systems through a gender-neutral lens, treating access to electricity or modern fuels as a technical problem with uniform effects across populations (Clancy & Dutta, 2005). This overlooked the deeply gendered patterns of energy access and use, as well as the structural inequalities that restrict women's ability to benefit equally from energy interventions.

Much of the existing gender-energy research has continued to focus narrowly on women's access to sustainable and reliable energy for household (reproductive) purposes, particularly in relation to cooking, heating, and lighting (Pueyo, Bawakyillenuo, et al., 2020). Within this household-centred framing, clean cooking has emerged as a critical but persistently under-addressed domain.

As indicated by the World Bank's latest estimates, approximately 2.4 billion people lack access to modern cooking services[3], with around 2.1 billion projected to remain in "cooking poverty" until 2030, compelled to rely on traditional fuels and technologies for cooking (Energy Sector Management Assistance Program (ESMAP), 2023). Sub-Saharan Africa stands out with the lowest rates of access to modern cooking services, highlighting significant regional disparities in energy access (Khanna et al., 2020). In efforts to promote clean cooking initiatives, a World Bank study found that female primary cooks in households using biogas reported spending less time on cooking tasks and expressing greater satisfaction with available leisure time (ESMAP, 2023). This underscores the transformative potential of clean cooking technologies in alleviating burdens traditionally shouldered by women and stresses the importance of recognising women as both beneficiaries and agents of change (Acuna Castillo et al., 2022).

Yet despite their significance, clean cooking interventions continue to suffer from insufficient gender analysis. Many projects fail to adequately capture time-use changes, health outcomes, or shifts in agency among women users, underscoring the need for better metrics and impact assessments (Acuna Castillo et al., 2022; ESMAP, 2023). Recognising this gap, initiatives, such as the World Bank's Clean Cooking Fund, launched in 2020 with a capitalisation of 500 million USD, aim to scale up investments and explicitly integrate gender-responsive designs into clean cooking interventions (Acuna Castillo et al., 2022).

The household sphere, and specifically the domain of cooking, thus remains a crucial frontier for gender-equitable energy access. Yet, the gender-energy nexus extends well beyond household energy needs. Although electrification is widely associated with improvements in women's economic opportunities, shifting women away from agricultural labour and expanding access to income-generating activities, empirical evidence suggests that these transitions are neither automatic nor uniformly beneficial (Asibey et al., 2021; Ngum & Kim, 2023; Pueyo, Bawakyillenuo, et al., 2020). The quality of newly created roles, the levels of earnings, and women's control over energy assets remain deeply constrained by structural gender inequalities.

[3] The World Bank introduces the concept of "Modern Energy Cooking Services (MECS)" within the framework of the World Bank's MTF. MECS considers various factors affecting cooking, such as exposure, efficiency, convenience, safety, affordability, and fuel availability (Khanna et al., 2020).

Insights from empirical studies further reveal that electrification projects often prioritise supply-side targets, such as connection numbers, while neglecting the gendered barriers that influence how energy is actually utilised (Asibey et al., 2021; Pueyo, Bawakyillenuo, et al., 2020; Pueyo, Carreras, et al., 2020). For instance, women's reliance on biomass persists even post-electrification, reflecting both affordability constraints and the lack of attention to productive energy needs beyond lighting and basic appliances. Initiatives that fail to recognise these differentiated needs risk deepening, rather than narrowing, gender gaps in economic empowerment (De Groot et al., 2017).

Thus, the household domain remains a critical, but incomplete, frame for addressing gender and energy access. Achieving substantive gender equity requires moving beyond household needs to consider how energy access shapes, or fails to shape, women's agency, entrepreneurship, and participation in broader economic transformations. The following section shifts the lens towards the gendered impacts of electrification beyond the domestic sphere.

3.3.2.2 Gendered impacts of electrification

As energy systems expand beyond basic household applications, the potential for electricity access to reshape economic livelihoods comes sharply into focus. In discussions of productive energy use, electricity has emerged as the dominant focus, largely due to its centrality in decentralised energy initiatives and its perceived role as a catalyst for productivity (Pueyo & Maestre, 2019). However, emerging evidence challenges the assumption that electrification alone guarantees equitable development outcomes. Studies show that access to electricity, particularly through decentralised systems, produces gendered impacts that are highly variable and context-dependent (Berthelemy, 2019).

While electrification initiatives are often evaluated through improvements in education and health metrics, their impacts on gender relations and economic empowerment receive far less systematic attention (Berthelemy, 2019). Statistical analyses increasingly reveal that improvements in energy access can yield both positive and negative effects on gender dynamics, with the extent and nature of these effects varying considerably across socio-economic and cultural contexts. Although electrifying income-generating activities holds significant potential to enhance household incomes, these opportunities remain unequally distributed. Structural factors often position women in less energy-intensive, lower-income

sectors compared to men, limiting their ability to fully leverage new energy services for economic advancement (I. Das et al., 2020).

Moreover, the challenges faced by women in leveraging electrification for economic empowerment are often amplified in fragile, conflict- and violence-affected (FCV) settings. In such contexts, where infrastructure is weaker and social vulnerabilities are heightened, the lack of reliable and affordable electricity services disproportionately hampers women's entrepreneurial efforts, constraining their ability to develop autonomous income streams and build socio-economic resilience (Maier et al., 2020).

Outside of FCV environments, broader reviews of decentralised energy interventions point to encouraging trends: access to electricity can enhance household incomes, facilitate reductions in agricultural labour, and promote women's participation in formal employment by enabling the use of time-saving, electrically powered appliances (I. Das et al., 2020; Köhlin et al., 2011). Certain studies highlight specific productive applications, showing that access to electricity for irrigation and agri-processing, such as through passive solar PV pumping and irrigation systems, can increase women's economic independence and resilience (I. Das et al., 2020; United Nations Environment Programme (UNEP), 2020). Further evidence from rural India demonstrates that renewable energy interventions, when strategically embedded in local value chains and supported through inclusive financing mechanisms, can substantially boost women's income, food security, and broader social well-being (Ingole, 2024). However, even in such promising cases, challenges related to scaling operations and ensuring access to concessional finance persist, suggesting that technological solutions alone are insufficient without structural support.

This dynamic is particularly well-illustrated by empirical evidence: Findings from a community-based micro-hydropower project in Ethiopia showed that while access to electricity yielded notable socio-economic benefits for communities at large, women's specific energy needs, particularly those related to productive use, remained largely unmet (Wiese, 2020). Women reported some improvements in flexibility and time savings, but these did not consistently translate into expanded income-generating opportunities or substantial reductions in workloads, revealing persistent blind spots in the design of rural electrification schemes.

Similarly, a study from Nepal found that while women expressed optimism regarding business prospects following electrification, actual enterprise creation

and formal employment gains remained minimal (Shrestha et al., 2023). In rural China, electrification improved women's perceptions of their social status but did not significantly increase their participation in non-agricultural wage employment (Hwang & Yoon, 2021).

Qualitative research from Zambia further corroborates these findings, emphasising that electricity access can indeed expand women's physical, economic, and social agency, but only when existing gender norms do not constrain how electricity is utilised (Kannan & Bessette, 2023). By putting women's own definitions of empowerment in the centre, this research highlights the need for energy interventions to go beyond economic metrics and explicitly integrate empowerment objectives into programme design.

Collectively, these findings emphasise that while electricity access offers a vital platform for socio-economic advancement, without intentional, gender-responsive design, the potential of energy interventions to catalyse empowerment remains under-realised. Yet women are not merely passive recipients of energy access; across diverse contexts, they are increasingly emerging as active agents of change, catalysing renewable energy deployment, driving last-mile distribution, and shaping new models of inclusive energy entrepreneurship. The following section explores this evolving landscape of women as drivers of renewable energy access, highlighting both the barriers they confront and the transformative potential they unlock.

3.3.2.3 Women as drivers of renewable energy access

The narrative around gender and energy access has gradually evolved from depicting women solely as beneficiaries to recognising them as pivotal actors in advancing renewable energy solutions, particularly in decentralised and off-grid contexts (I. Das et al., 2020; Ferroukhi et al., 2016; García-Baños & Renner, 2022; Jreich, 2024; Vinci et al., 2015). Programmes aimed at expanding access to clean energy increasingly highlight the critical role women play in delivering energy services, maintaining systems, catalysing demand, and securing financing (I. Das et al., 2020; Ferroukhi et al., 2016; Jreich, 2024; UNEP, 2020; Vinci et al., 2015)

Women's leadership in decentralised energy systems is not incidental: it reflects unique comparative advantages. Their strong community ties, social capital, and deep understanding of local needs position women as vital conduits for reaching underserved populations, particularly in last-mile markets (I. Das et al.,

2020; Vinci et al., 2015). For instance, initiatives like Solar Sister have demonstrated that empowering women as entrepreneurs in clean energy technologies, including solar lighting, clean cookstoves, and solar phone charging kits, can yield outsized developmental dividends (Ferroukhi, Nagpal, et al., 2019). Solar Sister alone has trained over 1,200 women entrepreneurs, who have collectively expanded energy access to more than 200,000 people, evidencing the transformative multiplier effects when women are positioned as energy access providers rather than mere consumers.

Similarly, the Women's Economic Empowerment initiative, which supports 3,730 women entrepreneurs across multiple countries, illustrates how female-driven energy access programmes can foster not only improved access outcomes but also stronger resilience at the household and community levels (ENERGIA, 2016). These initiatives also tend to generate broader co-benefits in education, food security, and health outcomes, as women often reinvest energy-related incomes into these critical spheres.

Beyond grassroots entrepreneurship, international programmes are beginning to explicitly design pathways for women's leadership in renewable energy deployment. Projects like EmPower: Women for Climate Resilient Societies, co-led by the United Nations Environment Programme (UNEP) and United Nations Entity for Gender Equality and the Empowerment of Women (UN Women), have advanced policy advocacy, capacity-building, and pilot projects in Bangladesh, Cambodia, and Vietnam, explicitly centring women's participation in energy transitions (UNEP, 2020). Likewise, the UN-led programme "Women's Entrepreneurship for Sustainable Energy" advocates for the establishment of local sustainable energy enterprises, also known as decentralised energy service companies or cooperatives (United Nations Entity for Gender Equality and the Empowerment of Women (UN Women) & UNEP, 2016). These entities operate with innovative business models that align energy service payments with the cash flows of consumers with low energy consumption and limited ability to pay.

Despite these promising developments, significant barriers persist. Discriminatory gender norms, unequal access to financing and training, and persistent stereotypes about women's technical capabilities continue to restrict the scale and impact of women-led energy initiatives (Harrison et al., 2024; Jreich, 2024). Even where women entrepreneurs succeed, they often face steeper hurdles than their male counterparts, including reduced access to business networks, limited

asset ownership, and difficulties in securing supplier credit or investor capital (Pollitzer & Lee, 2020; UNEP, 2020).

Nevertheless, women-owned energy enterprises tend to outperform male-owned ones in terms of customer satisfaction and service quality, and in many contexts, they are expanding faster (Harrison et al., 2024; Jreich, 2024). Recognising and strengthening women's role as renewable energy champions is therefore not only a matter of equity but a strategic imperative for accelerating universal energy access and achieving broader development goals.

By positioning women as agents rather than recipients, energy access programmes have the potential to transform not just energy systems but also the socio-economic fabric of rural and underserved communities. The next section builds on this analysis by examining how gender differences manifest in the patterns of productive energy use, where deep structural disparities continue to shape how energy translates into economic opportunity.

3.3.2.4 Gendered patterns of productive energy use

While women's increasing participation as agents of energy access is a promising development, deeper structural barriers continue to shape and often constrain how women benefit from electrification and productive energy initiatives. Recognising this, researchers have increasingly drawn on multidisciplinary perspectives to interrogate assumptions around energy and development. Rather than viewing energy as a neutral input, this body of evidence reveals its deeply gendered dimensions, shaped by occupational segregation, social norms, and systemic inequalities (Edomah et al., 2021; Ferroukhi, Renner, et al., 2019; Pueyo & Maestre, 2019).

At the enterprise level, women entrepreneurs face substantial and persistent challenges in leveraging energy for productive purposes. Barriers are not merely technical; they are rooted in structural constraints such as limited access to finance for energy assets, the predominance of informal business structures among women-owned enterprises, and societal norms that restrict women's mobility, ownership of appliances, and decision-making power (De Groot et al., 2017; Dutta et al., 2017; Edomah et al., 2021; Ferroukhi, Renner, et al., 2019; Pueyo & Maestre, 2019). In many cases, women entrepreneurs are required to have male guarantors to secure loans for purchasing energy technologies, further entrenching gendered financial exclusion (De Groot et al., 2017).

Against this backdrop, gender mainstreaming has emerged as a crucial strategy to correct systemic inequities. Moving beyond a technology-centric view, leading institutions now advocate for the integration of gender analysis across the entire life cycle of energy interventions, from programme design and financing to workforce development and monitoring (Asian Development Bank (ADB), 2012; Ferroukhi et al., 2018; Ferroukhi, Renner, et al., 2019; Fridriksson et al., 2019; Mohideen, 2018). Specific recommendations include establishing dedicated funding for women-owned enterprises, facilitating access to technical training, challenging gender stereotypes through the promotion of role models, and introducing gender-sensitive risk mitigation strategies within project design (André et al., 2021; Clancy & Dutta, 2005; ENERGIA et al., 2022; Ferroukhi et al., 2022; Ngoo & Kooijman, 2020; Orlando et al., 2018; Practical Action, 2023b; Schiffer & Yesutanbul, 2021; United Nations Development Programme (UNDP), 2004).

Empirical evidence supports the transformative potential of gender-inclusive approaches. A study conducted in Nepal and Sri Lanka concluded that an integrated gender approach, specifically within the water-energy nexus, can have positive gender equality and social inclusion outcomes (Mohideen, 2018). Nevertheless, evaluations reveal that gender considerations are often inconsistently applied, and many energy companies continue to operate without structured gender inclusion strategies, limiting the scale of potential impacts (Ceschin et al., 2023; Dutta et al., 2017).

Zooming into the patterns of productive energy use, studies across Tanzania, Ghana, and Myanmar reveal entrenched gender disparities. Men dominate higher energy-input sectors such as agriculture, fishing, and mechanical industries, while women are overrepresented in lower energy-intensity sectors like food preparation and petty trade (Asibey et al., 2021; Pueyo, Bawakyillenuo, et al., 2020; Pueyo, Carreras, et al., 2020; Pueyo et al., 2019). Even within the same sector, women are often confined to lower-income or lower-value segments of the value chain, such as cultivating subsistence crops rather than more lucrative cash crops or engaging in informal fish processing, while men dominate higher-income activities like commercial fishing (Pueyo, Carreras, et al., 2020; Pueyo et al., 2019). This is not merely a matter of occupational choice but reflects restricted access to credit, land, education, and energy technologies.

Energy carrier choice also mirrors these gendered divides. Businesses owned by men disproportionately use electricity for higher-value activities such as welding, vehicle repairs, and sawmilling, whereas women-owned enterprises

continue to rely heavily on biomass fuels like charcoal and firewood for cooking-related operations (Clancy & Dutta, 2005; Ngoo & Kooijman, 2020; Pueyo, Bawakyillenuo, et al., 2020; Pueyo, Carreras, et al., 2020; Pueyo et al., 2019). A nuanced study of rural non-farm enterprises in Ghana has shown that women primarily operate food vending businesses and rely on traditional solid fuels, while men dominate electrical, wood, and metal-based enterprises (Asibey et al., 2021). Another study suggests slight gender differences in energy choices, with men tending to diversify their energy carriers more than women (Ruggles et al., 2019).

Fuel switching towards modern energy carriers remains limited, particularly among informal businesses, where the higher cost of gas or electricity poses a significant barrier (Ruggles et al., 2019). Beyond cost considerations, factors such as women's education level, access to information, and intra-household decision-making dynamics crucially shape energy choices.

Importantly, while many studies report that women-owned businesses generally demonstrate lower electricity consumption and lower profit margins (Clancy & Dutta, 2005; Pueyo, Carreras, et al., 2020; Pueyo et al., 2019), emerging evidence challenges the inevitability of this trend. An evaluation of the Ghanaian Enterprise Development Programme found that electricity use positively correlated with profitability for both male- and female-owned enterprises, with women-owned businesses exhibiting even higher relative profitability gains once energy access barriers were addressed (Pueyo, Bawakyillenuo, et al., 2020).

However, a persistent structural bias remains in how productive energy interventions are conceptualised and implemented. A continued emphasis on electricity-based solutions, without a parallel focus on clean cooking energy, which remains central to many women-owned enterprises, risks reinforcing gendered disparities in energy access and benefit realisation (Ngoo & Kooijman, 2020; Pueyo et al., 2019).

To redress these inequities, the literature calls for a multi-pronged strategy: expanding access to tailored financial instruments, facilitating gender-sensitive energy management training, enhancing the reliability and affordability of energy supply, and fostering exposure to role models who challenge traditional gender norms in productive sectors (Clancy & Dutta, 2005; De Groot et al., 2017; Edomah et al., 2021; Pueyo et al., 2019; Ruggles et al., 2019). Investments in education, technology adaptation, and capacity-building must accompany energy access efforts to unlock the full productive potential of women entrepreneurs.

Building on these insights, the next thematic block focuses specifically on women entrepreneurs as end-users of energy services, assessing both the persistent barriers they face and the emerging opportunities to better align technology design, financing models, and policy frameworks with their needs.

3.3.2.5 Women entrepreneurs as energy end-users

Building on the understanding of gendered patterns of productive energy use, a more focused lens reveals how women entrepreneurs, as end-users of energy technologies and services, experience distinct opportunities and constraints. Their role is not only as beneficiaries but increasingly as critical actors in shaping demand, influencing markets, and redefining the contours of decentralised energy access.

The literature consistently highlights that the adoption of energy end-use technologies, whether in agriculture, agri-food processing, retail, or artisanal production, holds substantial potential for enhancing the productivity and sustainability of women-owned enterprises (ADB, 2012; Ferroukhi et al., 2016; Kooijman et al., 2020). Access to modern energy services can enable women entrepreneurs to diversify their activities, improve product quality, extend working hours, and reduce physical drudgery. However, the extent to which women can realise these benefits remains heavily shaped by structural barriers in accessing technology, finance, and decision-making spaces (ADB, 2012).

One critical issue is that women often have less influence over the acquisition of productive energy appliances, even when these technologies are primarily used for their own enterprises (Jreich, 2024; Kooijman et al., 2020). Purchasing decisions for appliances like refrigerators, mills, or sewing machines are frequently dominated by men, a dynamic that is particularly pronounced in contexts where financial contracts or asset ownership are traditionally male-dominated. As a result, data on appliance ownership often reflects male perspectives, masking the differentiated needs and preferences of women end-users (Kooijman et al., 2020).

Recent empirical surveys reinforce these dynamics. For instance, women constitute only about one-third of off-grid product end-users according to the latest datasets (Harrison et al., 2024), yet they are disproportionately represented among users of smaller, household-scale technologies such as solar lanterns. A survey on gendered consumer demand for productive use appliances found notable divergences: women expressed stronger preferences for sewing machines and

electric cookers, whereas men were more likely to prioritise solar water pumps and power tools (CLASP, 2020). This suggests that mainstream energy product portfolios often insufficiently address the sectors and applications where women entrepreneurs are most active.

Furthermore, women are often more inclined toward sustainability-oriented consumption behaviours. Studies show that women are more likely than men to value eco-labelled products, energy-efficient solutions, and localised supply chains (Jreich, 2024). Understanding and leveraging these differentiated consumer patterns offers an underutilised avenue for expanding productive use markets while supporting greater gender inclusion in energy and enterprise development.

Recognising these gaps, some initiatives have sought to adopt a gender-lens approach in energy programming. Investing in women-led companies, designing products tailored to women's physical and economic realities (e.g., adjusting for height, strength, ease of maintenance), and promoting inclusive financing mechanisms have all been proposed as strategies to better align supply and demand (Ferreri et al., 2022; Jreich, 2024; Soler et al., 2020). Some open-access guidelines offer women practical guidance and resources on how to assess different renewable energy technologies, enabling them to make informed choices based on their specific needs and circumstances (Rojas et al., 2012).

Despite these efforts, initiatives explicitly targeting women entrepreneurs as productive energy end-users remain limited. Available examples illustrate both the possibilities and the challenges. In one multi-district project across rural areas, women entrepreneurs received comprehensive support packages, including access to finance, technical and managerial training, and market development assistance, enabling them to better leverage renewable energy technologies for their enterprises (ENERGIA et al., 2022). Similarly, a study of women entrepreneurs operating micro-enterprises in India utilising electricity-powered and clean energy technologies, such as solar panels, solar-powered agricultural machinery, and electricity-run appliances such as sewing machines and e-rickshaws, for productive activities showed some interesting findings (Patnaik et al., 2021). While access to these energy technologies enabled women to expand their businesses and increase incomes, the study also points to persistent structural barriers, including limited access to finance, mobility constraints, and insufficient integration into formal policy schemes. It underscores the importance of embedding gender-inclusive financing and policy reforms within energy programmes to fully unlock the

economic and social potential of women-owned enterprises. However, such interventions are still rare relative to the scale of need.

Financial exclusion remains one of the most significant barriers. Despite growing capital flows into the renewable energy and clean cooking sectors, relatively few initiatives prioritise gender-responsive finance structures tailored to the needs of small women-owned enterprises (I. Das et al., 2020; Ferreri et al., 2022). Bridging this gap will require not only increased investment but also the creation of competitive financial ecosystems that drive innovation, lower transaction costs, and bundle energy services with business development support.

Ultimately, findings from the literature underscore that improving energy access for women entrepreneurs is not solely a matter of expanding infrastructure. It demands an ecosystem approach: ensuring appropriate technology design, enabling flexible financing, promoting skills development, and addressing embedded gender biases within energy markets and policy frameworks.

While the preceding sections have focused primarily on gendered disparities in energy access, usage patterns, and entrepreneurial opportunities, it is equally critical to examine the structures shaping who designs, delivers, and governs energy systems themselves. Gender inequalities persist not only in access to energy services or the capacity of women-owned enterprises to benefit from energy interventions but also extend deeply into the renewable energy workforce. Women remain significantly underrepresented in technical, leadership, and decision-making roles, risking the entrenchment of gender-blind policies even as the sector transitions toward cleaner, decentralised models. Addressing workforce disparities is thus not peripheral but central to achieving more equitable, inclusive, and sustainable energy transitions, as the following section elaborates.

3.3.2.6 Women's employment in the renewable energy sector

Employment within the renewable energy sector offers a critical lens through which to understand the persistence of gendered inequalities in emerging energy economies. According to IRENA, women constitute approximately 32% of the full-time workforce in the global renewable energy sector, a figure that, while higher than the oil and gas industry average of 22%, still reflects substantial underrepresentation (Ferroukhi, Renner, et al., 2019). Participation rates are not uniform across technologies: women's employment is highest in the solar photovoltaic (PV) industry, where they make up around 40% of the workforce

(García-Baños & Renner, 2022), but falls significantly in hydropower and wind sectors, where women constitute just 25% and 21% of employees respectively (Acuna Castillo et al., 2023; Ferroukhi et al., 2020).

Moreover, the gender gap widens considerably when disaggregating employment by role type. Women are disproportionately represented in administrative and non-technical positions, with significantly lower participation in technical, engineering, managerial, and senior leadership roles (Boyd et al., 2019; Ferroukhi et al., 2020; Ferroukhi, Renner, et al., 2019; García-Baños & Renner, 2022; Jreich, 2024; Ouziaux et al., 2021). Structural barriers such as persistent gender role perceptions, non-transparent hiring practices, and limited mentorship opportunities are commonly cited as major factors inhibiting women's career progression (Boyd et al., 2019; Cakmak et al., 2022; Ferroukhi et al., 2020; Ferroukhi, Renner, et al., 2019; García-Baños & Renner, 2022; Jreich, 2024). Cultural norms, workplace harassment, and sexist organisational cultures further exacerbate these challenges, creating environments where women face both overt and subtle obstacles to advancement (Boyd et al., 2019; Jreich, 2024; Ouziaux et al., 2021).

In response to these systemic disparities, a growing body of policy recommendations calls for the mainstreaming of gender perspectives across human resource strategies in the renewable energy sector. Proposed interventions include the collection and use of gender-disaggregated workforce data, the development of supportive networks and mentorship programmes, the implementation of gender-sensitive workplace policies, and the setting of voluntary or mandatory gender equity targets (Acuna Castillo et al., 2023; ADB), 2022; Boyd et al., 2019; Chase et al., 2017; Ferroukhi, Renner, et al., 2019; Jreich, 2024; Kraft et al., 2023; Orlando et al., 2018; Ouziaux et al., 2021). Expanding educational access for women and girls in science, technology, engineering, and mathematics (STEM) fields remains a particularly crucial lever for diversifying the renewable energy talent pipeline (Acuna Castillo et al., 2023; Ferroukhi, Renner, et al., 2019).

The preceding empirical review has illuminated the complex, multifaceted relationships between renewable energy access, productive energy use, and gender dynamics, revealing persistent inequalities as well as emerging opportunities. Across household energy needs, electrification impacts, women's agency in renewable energy access, patterns of productive use, entrepreneurial end-user dynamics, and workforce participation, a consistent theme emerges: energy systems, far from being gender-neutral, are deeply shaped by structural inequalities

that mediate who gains, who benefits, and how transitions unfold. While promising interventions are increasingly visible, the evidence underscores that energy access alone is insufficient to drive inclusive development outcomes. Addressing the underlying institutional, financial, and social barriers is imperative. Building on these findings, the following chapter critically reflects on the broader implications of the empirical evidence, identifies cross-cutting patterns, and proposes strategic priorities for advancing gender-responsive and transformative energy transitions.

3.4 Discussion

The findings from the quasi-systematic literature review underscore that the intersection between energy access, productive use of energy, and gender dynamics remains a critical but underdeveloped frontier within the broader sustainable development discourse. Although a growing body of research has advanced the understanding of how gender influences energy access and utilisation patterns (Clancy & Dutta, 2005; Pueyo et al., 2019; Pueyo & Maestre, 2019), much of the existing literature continues to prioritise household-level impacts, particularly concerning clean cooking, lighting, and basic domestic services (Acuna Castillo et al., 2022; ESMAP, 2023; Pueyo & Maestre, 2019). As a result, the gendered dimensions of productive energy use, particularly among women-owned enterprises, remain comparatively marginalised in empirical investigations and policy frameworks.

The review reveals that while productive uses of energy are increasingly recognised as central to rural development and energy access sustainability (Dagnachew et al., 2023; Schöne et al., 2024), electrification initiatives and decentralised energy projects are often conceptualised and implemented without adequately considering the differentiated constraints faced by women entrepreneurs (Pueyo, Bawakyillenuo, et al., 2020; Pueyo, Carreras, et al., 2020). Male-owned enterprises continue to dominate energy-intensive sectors such as agri-processing, carpentry, and fishing, while women are often confined to lower-energy, lower-return activities heavily reliant on traditional biomass fuels (Asibey et al., 2021; Pueyo et al., 2019). These patterns reflect structural inequalities, including restricted access to finance, land, technology, and business networks (De Groot et al., 2017; Edomah et al., 2021).

Importantly, where productive energy interventions have explicitly adopted a gender lens, promising outcomes have emerged. For example, the Ghanaian Enterprise Development Programme demonstrated that when electricity access was

combined with complementary business support, women-owned enterprises achieved notable profitability gains (Pueyo, Bawakyillenuo, et al., 2020). Similarly, research from rural Maharashtra, India, evidenced how decentralised solar-powered value chains can substantially boost women's income, food security, and empowerment (Ingole, 2024). However, these successes remain isolated cases rather than systemic trends. Without deliberate gender-responsive design, energy interventions risk reinforcing, rather than transforming, existing inequalities, as shown by empirical studies in Ethiopia (Wiese, 2020), Nepal (Shrestha et al., 2023), China (Hwang & Yoon, 2021), and Zambia (Kannan & Bessette, 2023).

A critical gap exposed by the review concerns the narrow technological framing of gendered energy needs. Most studies focus on electricity access as the principal vector for productive use, while thermal energy needs, especially for non-cooking productive activities, remain significantly overlooked (Ngoo & Kooijman, 2020; Pueyo, Carreras, et al., 2020; Pueyo et al., 2019; Pueyo & Maestre, 2019). This bias not only perpetuates the traditional stereotype of women's energy needs being confined to cooking and domestic work but also obscures women's broader economic roles in food processing, textile production, and other sectors where thermal energy is essential. By omitting these realities, much of the energy-gender literature inadvertently limits the scope of women's entrepreneurship within the energy transition narrative.

Similarly, few studies systematically differentiate among enterprise types, value chains, or regional sectors, often treating women entrepreneurs as a monolithic category. There is little recognition of how gendered constraints vary across ownership structures, business models, or local market conditions (Pueyo, Carreras, et al., 2020). Aggregating women's experiences risks erasing the specific barriers and opportunities faced by different categories of women entrepreneurs.

Moreover, the review highlights that most interventions remain technology-centric rather than systemic. The assumption persists that the mere provision of energy technologies, solar pumps, cold storage units, mills, will naturally translate into empowerment and economic upgrading (I. Das et al., 2020; United Nations UNEP, 2020). Yet multiple studies show that without parallel investments in gender-sensitive financing (De Groot et al., 2017), market access facilitation (Harrison et al., 2024), technical skills development, and supportive socio-cultural environments, productive use opportunities remain deeply unequal (ADB, 2012; Ferroukhi, Renner, et al., 2019; Pueyo et al., 2019; Pueyo & Maestre, 2019).

Recent evaluations further underscore that the neglect of longitudinal impact assessments compounds these challenges. As Bayer et al. (2020) and Rauschenbach et al. (2024) highlight, many energy access initiatives continue to measure success primarily through short-term outputs, such as connections or devices distributed, while higher-level outcomes, particularly those relating to women's business growth, economic resilience, and improvements in social mobility, understood as the advancement of women's socio-economic status over time, remain under-assessed (Rauschenbach et al., 2024). Consequently, the deeper developmental impacts of energy access on women's enterprises are insufficiently documented and poorly understood, limiting the sector's ability to design more transformative interventions.

The main gaps identified in the literature are summarised in Figure 6.

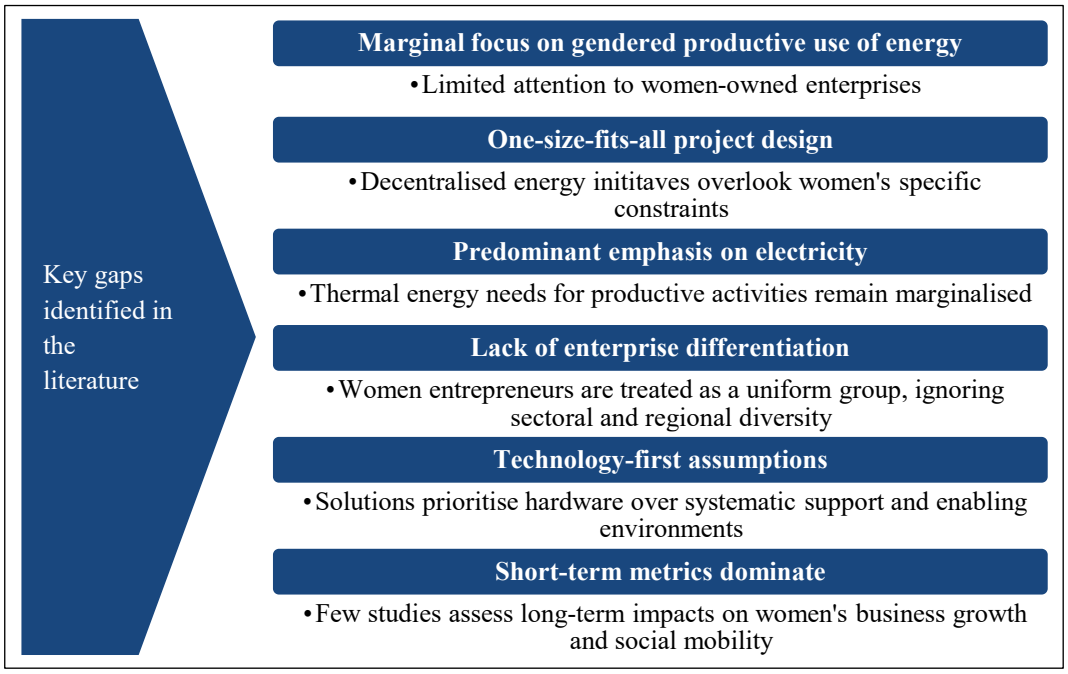

Figure 6. Key gaps identified in the scientific and grey literature

These observations have direct implications for the positioning and significance of the current research. By explicitly assessing the status of energy access among women-owned MSMEs across diverse ownership structures, sectors, and country contexts, this study addresses critical blind spots and data gaps that persist in the existing literature. Unlike much prior work, it adopts a disaggregated approach that recognises how gender intersects not only with enterprise ownership but also with sectoral demands, technology needs, and market positioning.

Importantly, this research also challenges the prevailing electricity-centric framing of women's energy needs. By systematically incorporating thermal energy demands, essential for agri-processing, food production, textiles, and other key sectors, it broadens the conceptual and empirical boundaries of productive use discourse and contributes to a higher penetration of renewable energy solutions in heating and cooling services for industrial sectors. In doing so, it contributes to advancing the literature on sustainable energy access and gendered productive use, offering a more context-sensitive understanding of what equitable energy transitions require.

3.5 Conclusions

The intersection of energy access, productive use, and gender has gained increasing attention within sustainable energy debates. However, the findings of this chapter underscore that the gender-energy nexus remains critically underexplored once moving beyond household consumption towards enterprise-level dynamics. While the importance of productive uses of energy is now widely recognised for rural development and energy sustainability, women's differentiated constraints and opportunities within this domain remain insufficiently examined.

The literature review revealed persistent gaps: a predominant focus on electricity to the neglect of thermal energy needs essential for key productive sectors; an over-aggregation of women entrepreneurs without accounting for sectoral or ownership structure variations; and a tendency to treat technology provision as a sufficient driver of empowerment, overlooking the necessity of integrated support in financing, skills, and market access. Moreover, the lack of longitudinal assessments and systemic gender-responsive design further limits the ability to capture real impacts on women's enterprise development, resilience, and socio-economic advancement.

Against this backdrop, the next phase of this research directly responds to these knowledge gaps. The following chapter shifts from literature synthesis to empirical investigation, examining which countries and productive sectors offer the most viable contexts for promoting sustainable energy access among women-owned enterprises.

Chapter 4

4. Selection of focus countries and industry sectors – Which contexts provide deeper insights into gendered productive use of energy?

4.1 Introduction

Building on the critical gaps identified in the literature review, this chapter marks a shift from conceptual synthesis to the empirical foundation of the research. The previous chapter highlighted that the productive use of energy by women entrepreneurs remains underexamined, particularly beyond the domestic sphere, pointing to a need for targeted, data-driven exploration. To address this, the current chapter draws on secondary quantitative and qualitative data to identify the most relevant countries and sectors in which these gendered energy dynamics can be meaningfully investigated.

This task takes on heightened urgency in light of persistent global energy inequalities. As of 2024, roughly 750 million people remain without electricity access, and over 2 billion still rely on polluting fuels for cooking, most of them residing in Africa (IEA, 2024b). These headline figures not only underscore the scale of the energy access challenge but also place Africa at the centre of global efforts to achieve SDG 7. Yet, behind these aggregated statistics lie deeply uneven regional patterns that require far more granular analysis.

Within Africa, electricity access is marked by striking disparities. While North African countries have surpassed 90% access, sub-Saharan Africa lags significantly behind, with an average access rate of just 55% (African Energy Chamber & RystadEnergy, 2024; The World Bank Group et al., 2023). This figure drops to 33%

in rural areas, with some countries reporting rates below 20% (African Energy Chamber & RystadEnergy, 2024).

The clean cooking deficit mirrors this troubling pattern. Access to clean fuels and technologies for cooking remains low across much of sub-Saharan Africa, averaging just 22% in 2023 (The World Bank Group et al., 2023). This stagnation severely constrains the health, environmental, and economic opportunities of millions, disproportionately affecting women, who continue to bear the brunt of energy poverty.

Electricity access and clean cooking access are thus often used as the principal metrics to assess progress towards energy inclusion. However, these indicators, while necessary, provide only a partial picture. They reveal the extent of basic household energy deprivation but do not capture the more complex dimensions of energy for productive uses, especially within MSMEs that underpin local economies.

Addressing this gap is especially critical given the overwhelming prevalence of small-scale and informal economic activity across Africa. As of 2023, International Labour Organization (ILO) data indicate that approximately 78% of workers in sub-Saharan Africa are self-employed, compared to 27% in the Middle East and North Africa (ILO, 2025). Among women, the gap is even more pronounced: 84% of female workers in sub-Saharan Africa are classified as self-employed, compared to 21% in the Middle East and North Africa. High rates of self-employment typically reflect the dominance of smallholder agriculture, informal trading, and micro-enterprise activity, often signalling limited formal wage employment opportunities and slower structural economic transformation.

While self-employment does not directly equate to formal MSMEs, it nevertheless highlights the critical role of small-scale entrepreneurship, particularly women-owned, in sustaining livelihoods and local economies across the continent.

Against this backdrop, this chapter addresses the research question: ***which African countries and industry sectors offer the most promising empirical grounds for investigating the gendered patterns of productive energy use within MSMEs?*** To this end, it systematically identifies high-potential countries and sectors that can serve as fertile ground for in-depth empirical inquiry.

Country selection is based on a systematic, quantitative assessment of available secondary data, prioritising contexts with a high density of MSMEs per capita and

a significant share of women-owned enterprises. This strategy ensures a targeted focus on environments where the intersection of gender, entrepreneurship, and energy access is most visible and where interventions may have outsized developmental impacts.

In parallel, industry sector selection is guided by a combination of quantitative indicators and qualitative assessments. Priority is given to sectors with substantial representation of women-owned businesses and diversified energy service needs, specifically, sectors demanding both thermal and electrical energy inputs, thereby maximising the relevance of renewable energy solutions for productive uses. This dual focus enables a more nuanced and context-sensitive exploration of the barriers, opportunities, and business models associated with enhancing energy access for women entrepreneurs.

Through this approach, the chapter establishes an empirical foundation based on secondary data analysis for the remainder of the study. The following section describes the materials and methods employed in the selection process, before presenting the final focus countries and industry sectors identified for in-depth investigation.

4.2 Materials and methods

This research adopts a systematic and structured approach to select the African countries and industry sectors offering a high potential for investigating the gendered dynamics of productive energy use among women-owned MSMEs. To ensure methodological transparency and replicability, the selection process is divided into two stages: country identification and sector prioritisation. Each stage applies specific selection criteria, draws on internationally recognised data sources, and critically reflects on the inherent limitations of secondary datasets. Notably, country selection relies exclusively on quantitative methods, while sector selection combines quantitative and qualitative approaches, allowing for both empirical grounding and contextual nuance, as summarised in Table 3.

Table 3. Data types, sources, and indicators used for country and industry sector selection

	Country selection	Industry sector selection	
Data type	quantitative	quantitative	qualitative
Source / Database	(1) MSME Economic Indicators Database (2) World Bank data	(1) World Bank Enterprise Surveys	(1) Technical reports (2) Sector-specific studies
Indicator	(1) MSME per 1,000 inhabitants (2) Share of women-owned MSMEs	(1) % of firms with female participation in ownership (2) % of firms with majority female participation in ownership	(1) Sector-specific energy needs (2) Feasibility of renewable energy adoption

Abbreviations: % = percent; MSME = micro-, small-, and medium-sized enterprise

4.2.1 Country selection

The selection of focus countries was conducted through a purely quantitative method. The primary data source was the MSME Economic Indicators Database 2019, compiled by the SME Finance Forum (2023), which provides comprehensive information on the number of formally registered MSMEs, national MSME definitions, enterprise size classifications, and employment data across 199 economies.

For Africa, countries without available or comparable MSME data were excluded, i.e., the Central African Republic, Chad, Comoros, Democratic Republic of Congo, Republic of Congo, Djibouti, Equatorial Guinea, Eritrea, Guinea-Bissau, Mauritania, São Tomé and Príncipe, Seychelles, Sierra Leone, and Somalia (SME Finance Forum, 2023). The database aggregates secondary data collected between July 2018 and December 2018, drawing from sources such as national statistical institutes, small business agencies, and research institutions. Although cross-

checked, slight inconsistencies in data collection methodologies and reference years across countries are acknowledged as a limitation.

Two core indicators guided country ranking: (1) the number of MSMEs per 1,000 inhabitants and (2) the share of women-owned MSMEs. This dual-criterion ensures that selected countries not only demonstrate entrepreneurial density but also exhibit meaningful gendered enterprise dynamics.

Given that the MSME Economic Indicators Database did not provide complete quantitative data on women-owned enterprises for all countries (SME Finance Forum, 2023), additional data were sourced from the database of the World Bank Group (2023) which provides sex-disaggregated ownership data across firms. Variations in definitions and data years were carefully considered, and a triangulation approach was applied to cross-validate and enhance the comparability of the resulting data.

This quantitative selection process enabled the identification of focus countries offering promising empirical settings for further investigation of the gender-energy nexus within the MSME sector. While integrating qualitative assessments at this early stage could have enriched the selection with additional context-specific nuance, doing so systematically across all African countries would have been methodologically unfeasible within the scope of this research. Given the need for broad comparability and transparency, the quantitative approach based on consistent, verifiable criteria provided a robust and appropriate foundation for narrowing the focus toward the most relevant contexts.

4.2.2 Industry sector selection

With the focus countries established through a structured quantitative methodology, attention now turns to identifying the most promising industry sectors where energy access, entrepreneurship, and gender most critically intersect. This sectoral identification followed a mixed-methods approach, combining quantitative data analysis with qualitative review of energy needs and technical feasibility.

Quantitative sex-disaggregated, sectoral analysis drew primarily from the World Bank Enterprise Surveys (The World Bank Group, 2023b). Conducted between 2013 and 2020, these surveys offer representative data on firm characteristics and performance across the formal private sector, excluding public utilities, financial services, and healthcare (International Finance Cooperation (IFC) & The World Bank Group, 2023; The World Bank Group, 2023b). Two indicators

were systematically analysed for each focus country: the percentage of firms with female participation in ownership and the percentage of firms with majority female ownership. These indicators facilitated identification of sectors with a substantial presence of women-owned enterprises.

Complementing the survey data, qualitative assessments were undertaken through a targeted review of technical reports and sector studies, notably by Hasanbeigi (2010), the International Renewable Energy Agency (IRENA) (2015), and UNDP (2004). This review focused on understanding sector-specific energy needs, particularly the balance between thermal, mechanical, and electrical energy demands, and the feasibility of renewable energy adoption in typical MSME operations.

Thus, while country selection was rooted exclusively in a quantitative ranking methodology, sector selection intentionally employed a mixed-methods strategy to capture both the statistical concentration of women entrepreneurs and the technical relevance for renewable energy transitions.

4.3 Results

Following the systematic methodology outlined above, this section presents the empirical outcomes of the country and sector selection processes. The findings provide the foundation for identifying where gendered dynamics of productive energy use in women-owned MSMEs can be most effectively investigated.

4.3.1 Country selection

Applying the quantitative selection criteria, seven African countries were identified as offering the most promising contexts for empirical analysis: Egypt, Ghana, Kenya, Malawi, Nigeria, Tanzania, and Tunisia.

The primary criterion for country selection was the density of MSMEs per 1,000 inhabitants, based on the assumption that higher entrepreneurial density offers richer ground for investigating productive energy uses (SME Finance Forum, 2023). All African countries for which data were available were ranked accordingly.

To further validate and strengthen the selection, a comparative analysis was conducted based on the share of women-owned MSMEs. Although not a primary selection criterion, this gender-related indicator served as an important

supplementary lens, aligning with the research's focus on women entrepreneurs. Wherever possible, figures on women's participation in enterprise ownership were cross-checked against regional and global averages, drawn from databases of the SME Finance Forum (2023) and the World Bank Group (2023a).

The final selection included the seven highest-ranked countries while excluding Senegal, Algeria, and Morocco, which, although ranked closely, displayed comparatively lower MSME densities and/or lower shares of women-owned enterprises. Interestingly, the geographic focus of the selected countries also closely mirrors the regional emphasis observed in existing gendered energy access literature, although some countries such as Tunisia, Malawi, and Egypt, identified here as having high research potential, are still underexplored in the empirical academic literature. This offers the opportunity to generate new insights from underrepresented contexts.

Importantly, most of the selected countries show shares of women-owned MSMEs that are either comparable to or above global and regional averages. According to the World Bank Group (2023a), the global average of firms with female participation in ownership is 33%, while sub-Saharan Africa's regional average stands at 28%, and the Middle East and North Africa (MENA) average is 19%. In this study, all selected countries, except Egypt, exceed the regional benchmarks, further validating the gender relevance of the focus countries.

This selection reflects a deliberate balance between entrepreneurial density and gender relevance. While countries such as Nigeria and Ghana exhibit exceptionally high MSME densities, others like Tanzania, Malawi, and Tunisia stand out for their high shares of women-owned enterprises. Egypt, despite lower gender participation rates, was included given its strategic importance in North Africa and to introduce geographic diversity into the analysis. The full data set adapted from the SME Finance Forum (2023) is provided in Appendix A, while Figure 7 summarises the key data underpinning the country selection.

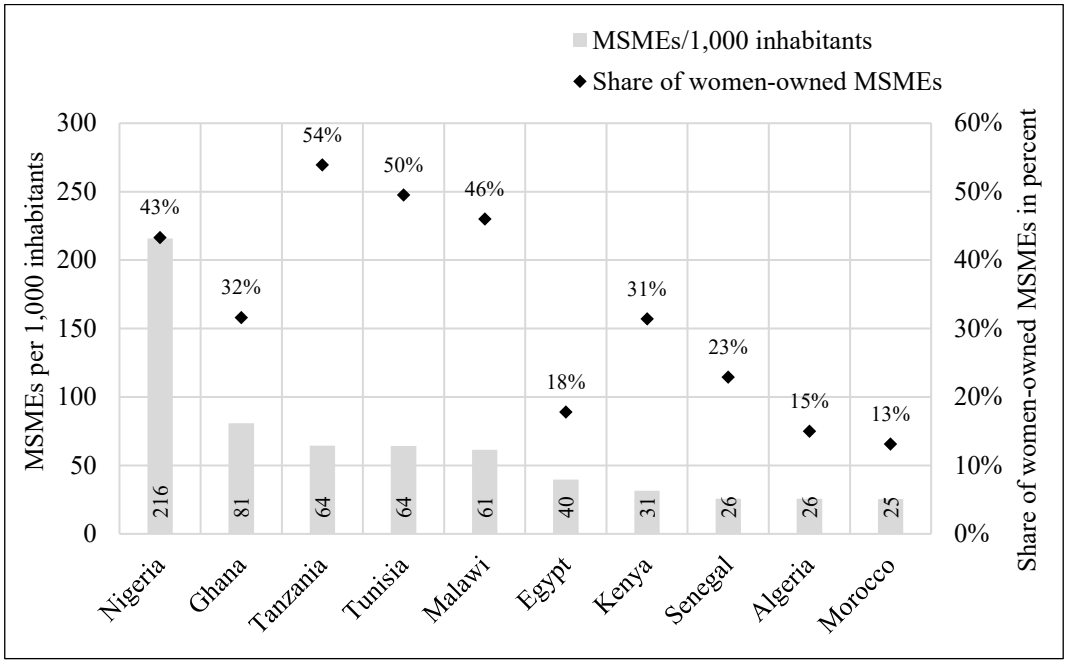

Figure 7. Density of formally registered MSMEs per 1,000 inhabitants across selected African countries

Notes: Data adapted from the MSME Economic Indicators Database 2019 (SME Finance Forum, 2023). Figures represent formally registered MSMEs and do not capture informal sector enterprises.

Moreover, the geographic diversity of the selected countries, spanning North, West, East, and Southern Africa, enables comparative analysis across different socio-economic, policy, and energy access landscapes, enhancing the broader applicability of the research findings.

In addition to density and gender considerations, it is important to note that definitions of MSMEs vary significantly across countries, typically based on thresholds of employee numbers, turnover, or asset size. In this research, the classification of MSMEs follows the respective national definition based on employee size, summarised in Table 4.

Table 4. Country definition of MSME by number of employees

Country	**MSME definition (number of employees)**			
	micro	**small**	**medium**	**large**

Egypt	1-4	5-49	50-99	>99
Ghana	1-9	10-30	31-100	>100
Kenya	1-9	10-49	50-99	≥100
Malawi	1-4	5-20	21-100	>100
Nigeria	1-9	10-49	50-199	≥200
Tanzania	1-4	5-49	50-99	>99
Tunisia	<6	6-49	50-199	>199

Micro-sized enterprises dominate the enterprise landscape across all selected countries. According to the MSME Economic Indicators Database, micro-enterprises account for over 99% of all MSMEs in Nigeria, 98% in Tunisia, 97% in Tanzania, 92% in Kenya, 89% in Egypt, and 81% in Malawi. In Ghana, micro- and small-sized enterprises together account for over 84% of the MSME sector (SME Finance Forum, 2023). This high concentration of micro-enterprises reinforces the importance of focusing on small-scale entrepreneurial dynamics when exploring the productive use of energy in African contexts.

Building on this foundation, the next section systematically identifies the priority industry sectors where gendered patterns of energy access and use are most critical to address.

4.3.2 Industry sector selection

Building on the identification of focus countries, the next stage of the research process aims to select the most relevant industry sectors for investigating the gendered dynamics of productive energy use among women-owned MSMEs. This sector selection followed a mixed-methods approach, combining quantitative analysis of enterprise ownership data with qualitative insights from the literature, to ensure both empirical robustness and developmental relevance.

Quantitative findings from the World Bank Enterprise Surveys provided the empirical starting point (The World Bank Group, 2023b). Across most of the selected countries, the food processing and textile and garments sectors consistently

emerged among the subsectors with the highest shares of women-owned enterprises. This trend was evident despite some country-specific nuances. In Ghana, the food sector exhibited the highest proportion of women-owned enterprises, with 36% of firms reporting majority female ownership. In Nigeria, the garments sector showed the highest share, at 39%, followed by other service-oriented sectors. Similar patterns were observed in Tanzania and Tunisia, where the garments sector ranked highest for female ownership participation, at 19% and 11%, respectively. In Kenya, the food sector recorded the second-highest level of female participation (20%) after hospitality and tourism. Egypt presented a slight deviation: while the food and textile and garments sectors showed notable female participation, they were outpaced by sectors such as non-metallic mineral products and chemicals. Nevertheless, the presence of women-owned enterprises in the food and textile sectors in Egypt remained substantial enough to warrant inclusion.

Sectoral disaggregation for Malawi was not available through the Enterprise Surveys, introducing a limitation for full cross-country comparability (The World Bank Group, 2023b). However, broader regional patterns and established insights from the literature strongly suggest that women's entrepreneurial activity in many sub-Saharan African contexts is heavily concentrated in food processing, small-scale manufacturing, and handicrafts (Jaiyeola & Adeyeye, 2021; UNDP, 2004). Additionally, both the agri-food and textile sectors are characterised by a predominance of micro- and small-sized enterprises (Rojas et al., 2012), which typically exhibit a higher share of women ownership compared to medium and large firms (UNDP, 2004). Although direct quantitative confirmation for Malawi is lacking, the selection of the food and textile sectors remains robust, supported by a triangulation of regional patterns and sector-specific gender dynamics. This sectoral focus is further illustrated in Figure 8, which summarises the share of firms with female participation and majority female ownership across the focus countries and selected industries.

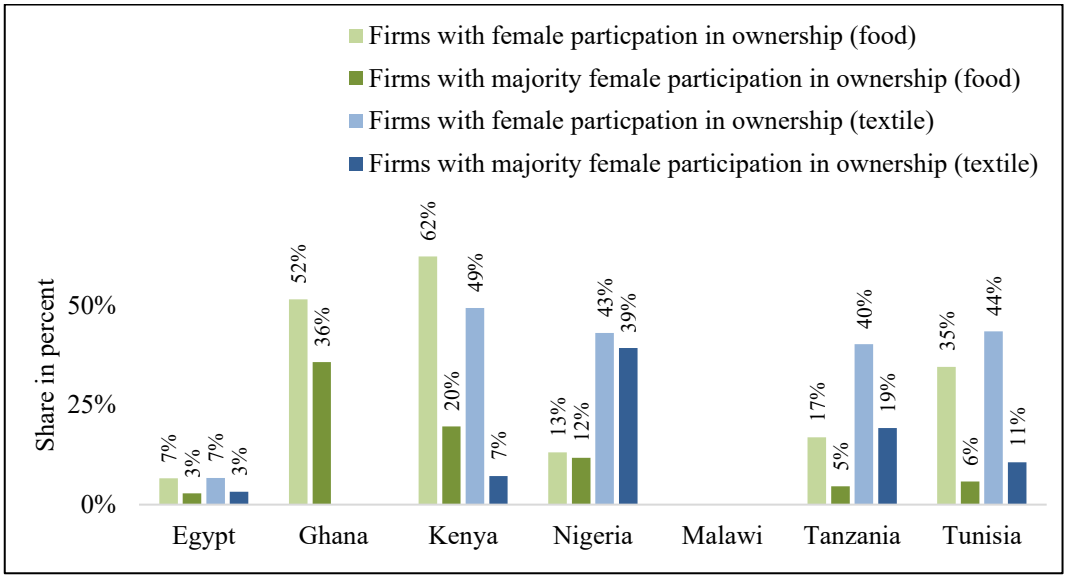

Figure 8. Share of firms with female participation in ownership across industry sectors and focus countries

The agri-food industry encompasses activities related to the processing, preserving, preparing, packaging, and marketing of agricultural and food products (Ferroukhi et al., 2016), while the textile industry includes the design, production, and distribution of yarns, fabrics, and garments (Hasanbeigi, 2010).

Both sectors involve diverse and intensive energy service needs, further enhancing their relevance for the present research. Productive operations in food processing and textile manufacturing typically require significant inputs of thermal, mechanical, and electrical energy (Bhatia & Angelou, 2015; Ferroukhi et al., 2016; Hasanbeigi, 2010; IRENA, 2015). Thermal energy is essential for drying, boiling, baking, dyeing, and ironing activities, with operational temperatures typically ranging from 30°C to 220°C in food processing and 30°C to 180°C in textile production. Mechanical energy supports activities such as milling, while electrical energy is critical for lighting, refrigeration, sewing, and packaging.

This complex energy demand structure creates substantial opportunities for the integration of decentralised renewable energy technologies and circular economy practices. Potential solutions include solar thermal systems for heat generation, solar PV installations for electricity needs, waste biomass-based systems, and emerging technologies such as solar-driven heat pumps (Hasanbeigi, 2010; Hinrichs-Rahlwes et al., 2021; IRENA, 2015). Furthermore, improving energy efficiency is particularly critical in the food and textile sectors, where operational

margins tend to be narrow and energy costs can account for a substantial share of total production costs (Hasanbeigi, 2010). The adoption of clean energy solutions and energy-efficient practices could therefore significantly enhance the productivity, profitability, and resilience of women-owned MSMEs operating in these industries.

4.4 Discussion

This chapter systematically identified seven African countries (i.e., Egypt, Ghana, Kenya, Malawi, Nigeria, Tanzania, and Tunisia) and two key industry sectors (i.e. agri-food processing and textiles) as promising contexts for investigating the gendered dynamics of productive energy use among women-owned MSMEs. The structured country and sector selection process ensures that the empirical focus aligns closely with where women's entrepreneurial activity and diversified energy needs intersect most meaningfully.

The country selection process was anchored in a quantitative methodological approach. Countries were ranked based on the density of formally registered MSMEs per 1,000 inhabitants (SME Finance Forum, 2023), supplemented by an assessment of women's participation in enterprise ownership (The World Bank Group, 2023a). This dual focus ensured not only a vibrant entrepreneurial landscape but also the gender relevance necessary for the research objectives. In parallel, sector selection drew on quantitative, sex-disaggregated enterprise ownership data from the World Bank Enterprise Surveys (The World Bank Group, 2023b), complemented by qualitative insights from the literature, to target industries with high female participation and complex energy requirements.

However, several limitations inherent to the available data sources and selection process must be critically acknowledged. First, data inconsistencies and gaps presented significant challenges. In many cases, the MSME Economic Indicators Database lacked gender-disaggregated enterprise ownership data (SME Finance Forum, 2023), necessitating supplementation from the World Bank Group (2023a). Methodological differences between these two data sources, such as definitions of women-owned MSMEs as per the SME Finance Forum (2023) versus firms with female share in ownership as per the World Bank Group (2023a), introduced uncertainties. Furthermore, sector-specific gender-disaggregated data were incomplete for certain countries, notably Malawi (The World Bank Group, 2023b). Although regional patterns and broader studies support the assumption that women entrepreneurs in Malawi are similarly concentrated in food processing and

small-scale manufacturing, the lack of direct quantitative confirmation limits the precision of cross-country sectoral comparisons. Additionally, the data years for the MSME statistics vary substantially across countries and are relatively outdated, ranging from 2012 to 2017 (SME Finance Forum, 2023), raising concerns about the accuracy of the data in rapidly evolving African economies, where demographic growth, economic diversification, and policy changes may have significantly altered the entrepreneurial landscape since the data were collected.

Second, the analysis is based on formal sector data. The database of the SME Finance Forum (2023) focuses exclusively on registered businesses, systematically excluding the informal economy, where a vast proportion of African women entrepreneurs operate (De Groot et al., 2017; Dutta et al., 2017; Ferroukhi, Renner, et al., 2019; Pueyo & Maestre, 2019). This underrepresentation is particularly problematic given that informal enterprises often face the most severe barriers to reliable, affordable, and productive energy use.

Finally, while this chapter successfully identifies priority countries and sectors, it does not yet assess the specific energy access realities within these contexts. Variables such as energy reliability, affordability, quality of service, prevalence of load shedding, and access to clean cooking technologies, factors known to critically shape the feasibility of productive energy use, are not captured in the macro-level selection indicators used here. These micro-level energy dynamics will be systematically investigated in the subsequent analyses to provide a more granular understanding of actual barriers and opportunities for women-owned enterprises. Where relevant, regional differences will also be taken into consideration. For instance, North African countries such as Tunisia and Egypt may present distinct configurations of opportunity and constraint, including comparatively stronger infrastructure but often more formalised and hierarchical business environments, where decision-making authority often remains male-dominated despite women's nominal ownership. Meanwhile, several sub-Saharan African countries may exhibit deeper energy infrastructure deficits but also stronger momentum in gender-focused programming. These contextual variations are recognised and will be explored further in the enterprise-level and policy-focused analyses that follow.

Figure 9 provides a visual synthesis of the country and industry sector selection process, highlighting known limitations affecting the scoping phase.

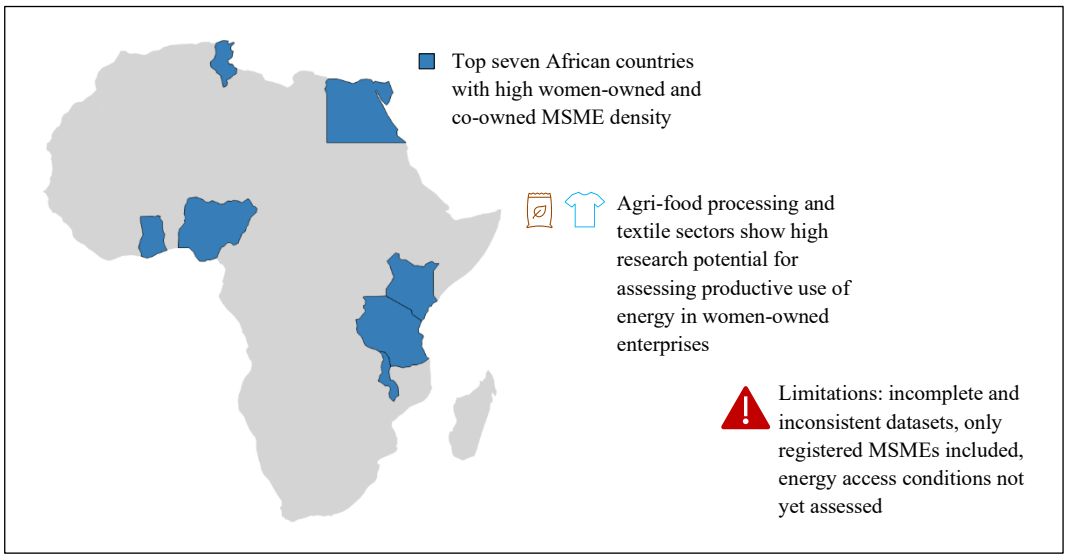

Figure 9. Overview of selected countries and sectors for investigating gendered productive use of energy in African MSMEs

Notes: The Africa map was produced using QGIS (QGIS.org) with country boundary data from Natural Earth (naturalearthdata.com). The map shows the following countries (listed in alphabetical order): Egypt, Ghana, Kenya, Malawi, Nigeria, Tanzania, and Tunisia. Boundaries do not imply official endorsement or political recognition. The map is for illustrative purposes only.

Despite these limitations, the selection approach adopted in this chapter represents a critical advancement for research on gendered productive use of energy in Africa. It moves beyond generic country categorisations by systematically combining entrepreneurial density and gender indicators, and it avoids a narrow focus on electricity alone by considering the multi-dimensional energy needs of targeted industries. By focusing on agri-food processing and textile sectors, the research aligns with industries that are labour-intensive and present substantial opportunities for decentralised renewable energy integration.

4.5 Conclusions

This chapter established the empirical groundwork for the research study by identifying where and how gendered patterns of productive energy use among women-owned MSMEs can be meaningfully explored. Through a quantitative selection process based on secondary data evaluation, seven African countries, Egypt, Ghana, Kenya, Malawi, Nigeria, Tanzania, and Tunisia, emerged as contexts where entrepreneurial density intersects significantly with women's economic participation, providing solid ground for analysis.

In parallel, a mixed-methods approach confirmed the relevance of the agri-food processing and textile sectors. These industries are not only central to women's enterprise activity across the selected countries but also embody diverse energy service needs, creating substantial opportunities for renewable energy integration and sustainable business model innovation.

Yet, the analysis also brought into sharp focus several critical data limitations, from definitional inconsistencies and outdated MSME statistics to the systematic underrepresentation of the informal sector. These gaps highlight the complexity of empirically capturing the realities of women's entrepreneurship and energy access in African economies, and reinforce the importance of nuanced, context-sensitive research approaches.

This chapter framed the landscape within which deeper investigation must proceed. By moving beyond purely macro-level indicators and prioritising sectors with productive energy needs, the research now transitions toward capturing primary evidence on the ground.

The next chapter initiates this empirical phase, presenting findings from a web-based survey conducted across women-owned and male-owned enterprises. Through this gender-disaggregated lens, the study will explore how ownership structure impacts access to, and productive use of, energy services.

Chapter 5

5. Assessing productive use of energy by ownership structure – To what extent does the gender in the ownership structure impact energy access and productive uses?

5.1 Introduction

Building on the empirical groundwork established in the previous chapter, this part of the research transitions from macro-level country and sector prioritisation to the first phase of primary data collection. It presents a detailed gender-disaggregated investigation into productive energy use among MSMEs operating within the agri-food processing and textile sectors across Egypt, Ghana, Kenya, Malawi, Nigeria, Tanzania, and Tunisia.

Recognising the critical evidence gaps identified earlier, particularly the lack of systematic analysis linking gender, enterprise ownership, and energy access beyond the household sphere, this chapter moves beyond aggregate statistics and sectoral averages. It seeks to capture more granular, enterprise-level realities: how women-owned and male-owned businesses access, utilise, and are constrained by energy services in their daily operations.

At the centre of the analysis lies a core research question: ***to what extent does the gender of the ownership structure influence energy access and productive uses in MSMEs?*** Understanding these dynamics is essential for designing energy interventions that are genuinely inclusive and that address the differentiated needs and opportunities faced by women entrepreneurs.

To address this, a web-based survey was developed and deployed across the selected countries, targeting enterprises operating in the previously prioritised sectors. The survey captured key dimensions, including business profiles, legal status, types of energy carriers used, as well as energy demand and expenditure.

The findings are structured in two complementary parts. The first part presents a comparative analysis of women-owned MSMEs across all seven focus countries, examining their energy access and productive energy use patterns. This broader cross-country lens provides a valuable snapshot of women's enterprise dynamics in different national contexts.

The second part delves into a more detailed gendered comparative analysis, made possible by the Nigerian sample. Unlike the other countries, where responses from male-owned enterprises were limited, Nigeria yielded a sufficiently diverse set of enterprises across female-, male-, and mixed-ownership types. This enabled the only robust gender-disaggregated comparison in the study, providing insight into how ownership composition shapes energy access and productive use patterns.

The chapter proceeds as follows: The next section outlines the materials and methods employed in the design, sampling, and deployment of the survey instrument, providing transparency regarding the data collection and analysis process. This is followed by the presentation of the survey results: first, the comparative analysis of women-owned enterprises across countries, and then the gendered productive energy use patterns identified within Nigerian MSMEs. The discussion section reflects critically on the findings, acknowledging methodological limitations and situating the results within the broader research objectives. The chapter concludes by summarising key insights and preparing the ground for the sector- and country-specific case studies that follow.

By moving into the empirical domain, this chapter marks a pivotal shift: from identifying promising contexts for intervention to directly examining how gendered ownership structures shape the realities of productive energy use on the ground.

5.2 Materials and methods

To move beyond the limitations of secondary data identified in earlier chapters, this study initiated its first phase of primary data collection through a web-based survey conducted between January 2023 and January 2024. This marked the start of an integrated mixed-methods strategy aimed at capturing ownership-related variations in energy access and productive use among MSMEs operating in the food

and textile sectors across seven African countries: Egypt, Ghana, Kenya, Malawi, Nigeria, Tanzania, and Tunisia. The survey was designed to generate a gender-disaggregated dataset capable of uncovering ownership-related differences in energy access and utilisation patterns within these key industries, thereby contributing to the existing literature on gendered dimensions of productive energy use.

The overall approach to data collection and analysis is summarised in Figure 10 and is further detailed in the subsequent sections.

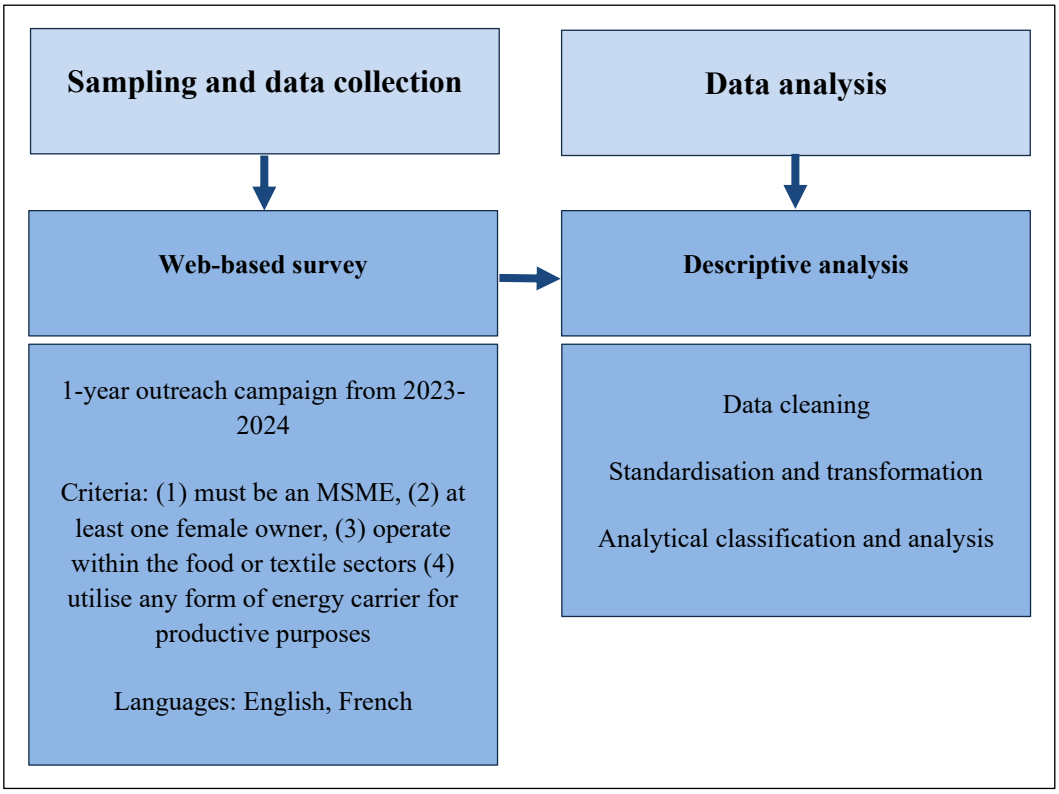

Figure 10. Overview of sampling and data collection, as well as data analysis used for the web-based survey

5.2.1 Sampling and data collection

The sampling strategy was underpinned by a year-long outreach campaign ranging from January 2023 to January 2024 and designed to maximise the reach and diversity of respondents. In each country, contact was initiated with a variety of entities, including governmental agencies, non-governmental organisations (NGOs), intergovernmental bodies, development institutions, business

associations, and sector-specific private firms, believed to maintain databases of or regular contact with women and men entrepreneurs.

At the outset, it was clearly communicated to all contacted entities that eligible research participants needed to fulfil specific pre-established criteria: (1) enterprises had to be classified as an MSME, (2) have at least one female owner, (3) operate within the food or textile sectors as defined by the International Standard Industrial Classification of All Economic Activities (ISIC), and (4) utilise any form of energy carrier for productive purposes.

The outreach campaign sought to compile a broad database of enterprises fitting these sectoral and ownership profiles, thereby creating a targeted but diverse sampling pool. It is important to clarify that achieving statistical representativeness was not the aim of the sampling strategy. Rather, the priority was to assemble a sufficiently diverse and contextually relevant respondent group to enable a meaningful gender-disaggregated analysis of productive energy use patterns across the selected countries and sectors.

The web-based survey was created using Google Docs and was made available in English and French to accommodate linguistic diversity. During the broader outreach campaign, the principles of voluntary participation, data protection, and confidentiality were communicated to all institutional partners and prospective participants, adhering to ethical standards. Following scientific standards for digital survey design, such as outlined by Andrews et al. (2003) and Regmi et al. (2016), the survey included an introductory statement that explained the study's purpose, provided basic instructions, indicated the estimated time required to complete the questionnaire, and concluded with a note of appreciation to participants for their time and contribution. Sensitive questions were paired with "prefer not to say" options to uphold respondent comfort and autonomy. Furthermore, no personally identifiable information, such as names, email addresses, or IP addresses, was collected, ensuring full anonymity of participants. The survey was optimised for accessibility across various devices and low-bandwidth environments, reflecting ethical standards in conducting inclusive and secure research.

The questionnaire was intentionally concise, consisting of two parts with a total of 14 questions, and was designed to take no more than 15 minutes to complete. The first section captured enterprise characteristics, including the country of operation, gender of ownership or co-ownership, number of employees, formal or informal status, sector (food or textile), type of business activity, and average

monthly production output. The second section focused on energy-related parameters, such as the types of energy carriers used, average monthly electricity and fuel demand, and annual energy expenditure. To maximise accessibility and ease of use, questions were designed to be as simple and straightforward as possible. Explanatory notes accompanied the survey where needed to assist participants in selecting appropriate answers. A full overview of the survey structure, question types, and guidance notes is provided in Appendix B.

5.2.2 Data analysis

The survey data were analysed using a descriptive cross-sectional study design, complemented by elements of analytical cross-sectional analysis (Aggarwal & Ranganathan, 2019; Siedlecki, 2020). Descriptive research was employed to depict the distribution of variables across the dataset, such as enterprise size, ownership structure, and energy consumption levels, while analytical cross-sectional techniques allowed for the exploration of relationships between gender ownership and productive energy use, without claiming causality. The study remains observational in nature, describing existing patterns and highlighting associations for further exploration. The analytical procedure followed a systematic, chronological structure comprising data reduction, display, transformation, correlation, and interpretation (Peterson Combs & Onwuegbuzie, 2010).

The initial data cleaning phase involved removing duplicate responses and excluding enterprises that did not meet the MSME size thresholds, typically measured in the number of employees. This ensured that only relevant businesses were retained for further evaluation, aligned with the study's research scope.

Subsequently, to enable meaningful cross-country and inter-sectoral comparisons, the cleaned dataset was subjected to a structured process of standardisation and transformation. First, all energy carriers were classified into two overarching categories: electric and non-electric energy. The former encompassed all mechanical and electrical energy needs, met through combinations of grid electricity, solar PV systems, or diesel and petrol generators. The latter included all thermal energy needs, assumed to be met through LPG, natural gas, kerosene, biomass, or other thermal carriers.

Second, and to provide an additional analytical layer beyond the survey's original design, enterprises were also classified according to their energy access type, specifically, whether they operated grid-tied or off-grid. Enterprises that

reported no use of grid electricity were first isolated, and their self-reported geographical locations were cross-referenced with the Africa Grid Database (The World Bank Group, 2017) to determine the availability of grid infrastructure. In instances where grid coverage theoretically existed but enterprises did not report connection, it was cautiously assumed that the enterprise operated effectively off-grid. While this geospatial cross-verification process introduced a degree of interpretive uncertainty, it enabled a practical distinction between grid-dependent and grid-independent energy users.

Once energy carriers were categorised, all reported energy consumption values were standardised into a common metric of kilowatt-hours (kWh), ensuring consistency across enterprises. This standardisation was based on the use of lower heating values (LHV) for fuels, typical fuel densities, and assumed equipment efficiencies, as detailed in the corresponding technical references (Ballard-Tremeer & Jawurek, 1996; Ekouedjen et al., 2020; Garg et al., 2006; Islam et al., 2022; Kanase et al., 2021; Statistics Netherlands, 2025; Stiel & Skyllas-Kazacos, 2012). Likewise, production outputs were standardised in kilogrammes (kg) (Kubkomawa, 2017; Nepomuceno et al., 2014; Njoro, 2003; Olayemi et al., 2011; Tash, 2015), and financial data were harmonised in US dollars (USD), based on average 2022 exchange rates obtained from respective central banks and international exchange data services (Central Bank of Egypt, 2023; Central Bank of Ghana, 2023a; Central Bank of Kenya, 2023a; Central Bank of Nigeria, 2023; Central Bank of Tunisia, 2023; Xe, 2023a, 2023b). Appendix B provides more detail on the conversion factors applied.

For the final analytical step, the cleaned and standardised dataset was disaggregated according to the gender structure of enterprise ownership. Three categories were used to classify enterprises with female participation: (1) sole female ownership, (2) female-female partnerships, and (3) gender-diverse partnerships[4]. However, to enable a comparative gender analysis that also included male-only ownership structures, the study focused primarily on Nigerian data. Only Nigeria yielded a sufficient number of meaningful responses across female- and male-ownership structures, while other countries presented too few male-owned enterprise responses to permit comparative evaluation. Consequently, for the

[4] The web-based survey instrument was designed to allow participants to select gender identification beyond binary categories, offering the options of "female", "male", "other", or "prefer not to say". For the final analysis, enterprises with co-ownership structures that included combinations such as female-male, other-male, or female-not specified were categorised under the umbrella term "gender-diverse" enterprises.

Nigerian sample, two additional categories were introduced: (4) male-only ownership and (5) male-male partnerships.

While the web-based survey offered an efficient mechanism for capturing broad patterns of energy use and enabling an initial gender-disaggregated analysis, it was intentionally designed as only the first step within the broader research methodology. Given its necessarily streamlined structure, the survey provided valuable breadth but limited depth regarding the technical, financial, and operational dimensions of energy use. To address these limitations and further strengthen the empirical foundation, a second, more in-depth phase of primary data collection was undertaken, consisting of on-site energy audits conducted through face-to-face interviews with enterprise owners. This research part is presented in Chapter 6.

Through this multi-phased and systematic approach, the research builds a basis for analysing gendered energy dynamics among African MSMEs, while transparently acknowledging the inherent limitations of remote, survey-based data collection.

5.3 Results

Building on the methodology outlined previously, this chapter presents the findings from the web-based survey conducted among MSMEs operating within the food and textile sectors across Egypt, Ghana, Kenya, Malawi, Nigeria, Tanzania, and Tunisia. The analysis proceeds in two main stages, aligned with the dual objectives of the survey: first, assessing the productive use of energy across enterprises with female participation in ownership across all countries, and second, conducting a deeper gender-disaggregated comparison based on the richer dataset available from Nigeria.

The first part of this chapter (Section 5.3.1) examines the business profiles, legal statuses, and productive energy use patterns of women-owned enterprises across the seven countries. This comparative analysis highlights cross-country and sectoral differences in enterprise characteristics, energy access conditions, and energy usage strategies among businesses where women are primary or co-owners.

The second part of this chapter (Section 5.3.2) narrows the focus to Nigeria, where the survey yielded a sufficiently large and diverse set of enterprises owned by women, men, and mixed-gender partnerships to allow for a comparative gender analysis. This more granular comparison explores whether and how enterprise

ownership structure influences productive energy use patterns within a specific national context.

5.3.1 Findings: Productive energy use in women-owned enterprises across focus countries

The first analytical stage focuses on enterprises that feature women as sole owners, co-owners in female-female partnerships, or co-owners in gender-diverse partnerships across the seven focus countries. The aim is to characterise these businesses in terms of their sectoral engagement, ownership models, legal registration status, size, and patterns of energy access and utilisation. By establishing these foundational profiles, the analysis seeks to uncover early evidence of how gender dynamics intersect with productive energy access and enterprise development across different African contexts.

5.3.1.1 Sample overview

Following the data cleaning process outlined earlier, a total of 65 enterprises featuring female participation in ownership were retained for analysis. The geographic distribution of the sample reveals that Nigeria constitutes the largest share, contributing 40% of all valid responses. Kenya, Malawi, and Tunisia follow with 19%, 15%, and 11% of the sample, respectively, while Egypt and Ghana contributed smaller shares, each around 5-6%. Although this distribution reflects the varying levels of survey response rates across countries, it still captures a broad range of regional dynamics across North, West, East, and Southern Africa.

Sectoral engagement among the sample enterprises is strongly concentrated in the food industry: nearly 79% of respondents operate within ISIC-defined food-related sectors, encompassing activities such as crop and animal production, fishing and aquaculture, food manufacturing, and food service activities. The remaining 21% of enterprises are engaged in textile-related sectors, including textile production, wearing apparel, and leather goods manufacturing. The predominance of food sector enterprises is consistent across all countries, reflecting broader patterns of women's entrepreneurship in Africa, where food processing activities are often a primary site of economic participation.

Regarding ownership structures, the sample exhibits a near-even split between different gender-based models. Sole female ownership accounts for 31% of enterprises, female-female co-ownership for another 31%, and gender-diverse

enterprises for 38%. However, important sectoral distinctions emerge when disaggregating these ownership structures, as shown in Table 5. In the food sector, enterprises are relatively evenly distributed across the three ownership categories, although a slight majority (47%) involve gender-diverse co-ownership. In contrast, the textile sector is overwhelmingly dominated by enterprises exclusively owned by women: 93% of textile businesses are either solely owned by a female or co-owned by females. This suggests that food enterprises tend to display more gender-diverse ownership structures, whereas textile enterprises appear more vertically segmented, with ownership concentrated predominantly among women.

Table 5. Distribution of enterprises by industry sector and gender-based ownership structure across focus countries

Industry sector	Gender-based ownership structure			Total
	Sole female	Female-female	Gender-diverse	
Food sector	27%	26%	47%	100%
Textile sector	43%	50%	7%	100%

A detailed breakdown of business activity types further reveals significant differences across ownership models. Gender-diverse enterprises tend to specialise in a narrower range of activities, primarily manufacturing food products (64%) and crop and animal production (24%). Conversely, enterprises solely owned by women or involving female-female partnerships exhibit a broader diversification across food manufacturing, wearing apparel production, fishing and aquaculture, and food service activities. This greater diversification may indicate higher levels of entrepreneurial flexibility and adaptation among exclusively women-owned businesses.

When considering MSME size based on the number of employees, the sample is heavily skewed toward micro-enterprises: 65% of respondents fall into this category, while 35% qualify as small enterprises. No medium-sized enterprises were captured in the survey. This distribution reflects the broader structure of the African MSME landscape, where micro-businesses dominate, particularly among women entrepreneurs. Interestingly, ownership structure again appears to influence enterprise size: while 75% of sole female-owned enterprises and 70% of female-female co-owned enterprises are micro-sized, gender-diverse enterprises show a

more balanced distribution, with 52% classified as micro-sized and 48% as small-sized enterprises. This suggests that gender-diverse ownership structures may correlate with slightly larger enterprise scales.

A full breakdown of the number and share of respondents by country, industry sector, gender-based ownership structure, and enterprise size is provided in Appendix B.

Turning to legal registration status, the data reveal that approximately 62% of enterprises are formally registered, while 11% operate without registration, and the remaining 27% either preferred not to disclose their registration status or did not respond. Disaggregating by sector, registration rates are similar across food (61%) and textile (64%) enterprises, suggesting that sectoral engagement does not significantly influence formalisation tendencies.

However, ownership structure appears to play a notable role. Enterprises solely owned by a female display the highest level of informality or reluctance to disclose: only 30% of sole female-owned businesses are registered, while 10% are not registered, with a full 60% opting not to disclose their status. In contrast, enterprises with a female-female partnership demonstrate a higher registration rate of 65%, and those with gender-diverse co-ownership reach a registration rate of 72%, with only 20% across both ownership structures choosing not to disclose. This pattern may reflect broader challenges faced by sole female-owned enterprises in navigating regulatory and formalisation processes, potentially linked to resource constraints, lower access to business development services, or greater sensitivity to formal sector scrutiny.

In sum, the business profiles and legal statuses of enterprises with female participation across the focus countries present several key patterns. Women entrepreneurs are strongly concentrated in the food sector, though textile businesses show stronger exclusive female ownership. Gender-diverse co-ownership structures appear to correlate with larger enterprise size and higher formalisation rates, while women-only businesses display greater diversification but also higher rates of informality or opacity regarding legal status. These findings offer important contextual grounding for understanding how ownership structure may influence productive energy use patterns, a theme explored in the following section.

5.3.1.2 Energy use patterns in women-owned enterprises

Building upon the business profiles discussed previously, this section explores the energy access realities and usage patterns among enterprises with female participation in ownership across the seven focus countries. The findings reveal significant heterogeneity in energy access types, energy carrier combinations, levels of productive energy demand, and energy expenditure, influenced both by sectoral affiliation and by the ownership structures of the enterprises.

Energy access and off-grid prevalence

Across the overall sample, approximately 25% of enterprises were identified as operating without any grid electricity connection and are therefore classified as functioning off-grid. This rate is noteworthy when compared to regional electrification benchmarks: in sub-Saharan Africa, around 19% of urban residents and 70% of rural residents still lack access to the grid (The World Bank Group et al., 2023). Among the focus countries, Nigeria contributed the majority of off-grid enterprises (62.5%), followed by Kenya (19%), Tunisia (12.5%), and Malawi (6%). No off-grid enterprises were recorded in Egypt, Ghana, or Tanzania within the sample, though it should be noted that response rates in these countries were relatively low.

Interestingly, the off-grid status was not always a direct function of infrastructure absence. Geospatial cross-referencing with the Africa Grid Database (The World Bank Group, 2017) revealed that approximately 62.5% of enterprises operating without grid electricity were, in fact, located within areas theoretically covered by the national grid. Despite nominal proximity to grid infrastructure, these enterprises remained disconnected, primarily due to barriers such as prohibitive connection costs, unreliable service quality, or context-specific factors like administrative hurdles or informal settlement status. Another 12.5% of enterprises fell into an “uncertain access” category, where incomplete location data, only specified at the broader state or regional level, meant partial intersection with grid coverage could not be definitively confirmed. Only 25% of off-grid enterprises were situated in areas entirely lacking existing grid infrastructure.

A closer examination of the business profiles reveals that the majority of these off-grid enterprises are concentrated in sectors typically characterised by intensive energy needs: 44% are engaged in food manufacturing (e.g., rice and flour milling, palm oil production), 31% in crop and animal production (such as livestock

breeding and plantations), and 19% in fishing and aquaculture. Only one enterprise (6%) was active in the manufacture of wearing apparel.

Energy sourcing among these enterprises reflects the operational realities of their off-grid status. Approximately 75% rely primarily on self-generation technologies, using diesel or petrol-fuelled generators and, increasingly, solar PV systems to meet their electricity and mechanical energy demands. The remaining 25% focus on thermal energy needs, drawing on LPG, natural gas, kerosene, and biomass fuels such as briquettes, firewood, and charcoal.

Disaggregating by ownership structures, it becomes evident that energy access varies across different forms of enterprise ownership. Gender-diverse enterprises are overrepresented among off-grid operations, with 36% of such enterprises operating off-grid, compared to 20% for female-female partnerships and 15% for sole female-owned businesses. This may reflect a greater willingness or ability among gender-diverse ownership structures to navigate the technical, financial, and managerial challenges associated with off-grid energy solutions.

As shown in Table 6, overall, these patterns underscore a critical insight: physical grid presence alone does not guarantee meaningful energy access. Structural and economic barriers continue to leave many productive enterprises functionally off-grid, compelling them to rely on autonomous, often costly and less sustainable, energy solutions.

Table 6. Characteristics of off-grid operating women-owned enterprises across focus countries

Country	Location	Energy carrier	ISIC category	Business activity	Gender-based ownership structure	Existing grid line
Kenya	Mashuru, Kajiado County	Petrol, Solar PV, LPG	1	Livestock and breeding	Gender-diverse	No
Kenya	Ruiri, Meru County	Solar PV	1	Vegetable crops	Sole female	Yes
Kenya	Nairobi, Nairobi City County	Solar PV, Diesel	1	Vegetable crops	Gender-diverse	Yes
Malawi	Lilongwe, Central Region	Other	10	Flour milling	Gender-diverse	Yes
Nigeria	Abeokuta, Ogun State	LPG, Other	3	Fish drying	Female-female	Yes
Nigeria	Ijebu Ode, Ogun State	Petrol, LPG	3	Fishing and rearing	Gender-diverse	Yes
Nigeria	Ibogun Olaogun, Ogun State	Diesel	10	Palm oil production	Gender-diverse	Yes
Nigeria	Lafia, Nasarawa State	Diesel, other	10	Rice milling	Gender-diverse	Yes
Nigeria	Abeokuta, Ogun State	Diesel, Solar PV, Other	10	Palm oil production	Gender-diverse	Yes

Nigeria	Ogbomosho, Oyo State	Diesel	10	Rice milling	Female-female	No
Nigeria	Ogun State	Diesel	10	Rice milling	Gender-diverse	Uncertain
Nigeria	Ota, Ogun State	Biomass, Other	3	Fish drying	Sole female	Yes
Nigeria	Borno State	Solar PV	14	Flour milling and fish drying	Sole female	Uncertain
Nigeria	Yola North, Adamawa State	Biomass	10	n/a	Female-female	Yes
Tunisia	Kebili, Nefzaoua region	Solar PV, Other	1	Plant crops	Female-female	No
Tunisia	Kebili, Nefzaoua region	Other	1	Dates and palm trees	Gender-diverse	No

Energy carrier diversity

Turning to energy carrier use, clear sectoral and ownership-based trends emerge. In the food sector, a majority of enterprises (53%) reported using two distinct energy carriers, typically a combination of grid electricity and fuel. In contrast, the textile sector demonstrated a heavier reliance on a single energy carrier, predominantly grid electricity (71%). This sectoral divide reflects the different energy service profiles of the two industries: food processing activities typically require both thermal and electrical/mechanical energy inputs, whereas textile enterprises often operate with primarily electric processes such as sewing and ironing.

Ownership structure further nuances these patterns. Sole female-owned and female-female co-owned enterprises showed similar profiles: about 45% use two energy carriers, and 40% rely on a single carrier. In contrast, gender-diverse

enterprises exhibit a more diversified energy portfolio: 40% use two energy carriers, while a striking 32% engage three or more energy carriers, twice the rate of multiple carrier use observed among women-only enterprises. This suggests that gender-diverse ownership structures may be associated with higher levels of technological or operational complexity in energy sourcing strategies. A more detailed breakdown of energy carrier use by gender-based ownership structure and disaggregated by country can be found in Appendix B.

Solar PV technology, either as a standalone or hybrid system, also featured in the energy mix, albeit at modest levels. About 28% of gender-diverse enterprises, and 20% of female-female co-owned enterprises, incorporated solar PV into their energy systems, compared to just 10% of sole female-owned enterprises. The adoption of solar PV, though still relatively limited, signals emerging opportunities for decentralised renewable energy uptake among women entrepreneurs, particularly in food processing where diversified energy needs make hybrid solutions more attractive.

A deeper examination of fuel use patterns provides additional insights. Diesel emerged as the dominant fuel across the sample, used by 42% of enterprises with productive fuel needs, followed by biomass fuels (firewood, charcoal, briquettes) at 38% and LPG at 27%. Petrol was used by 13% of enterprises, while natural gas, reflecting country-specific energy markets such as Egypt and Tunisia, accounted for 11% of productive fuel use. Kerosene usage was rare, reported by only a single enterprise in Kenya.

Gender-disaggregated analysis reveals distinct patterns across ownership structures. Sole female-owned enterprises exhibit a stronger orientation toward cleaner fuels: 31% use LPG for productive activities, 25% utilise natural gas, and 19% rely on biomass, with diesel and petrol playing only minor roles. This suggests a tendency toward adopting cleaner and often more manageable energy carriers, possibly reflecting both resource constraints and differentiated technology preferences. Similarly, female-female co-owned enterprises demonstrate an equal reliance on LPG and biomass (each at 33%), followed by diesel (27%), with minor shares using natural gas. In contrast, gender-diverse enterprises show a markedly different fuel profile, relying predominantly on diesel (45%) and biomass (31%), while LPG and petrol are used to a lesser extent. This heavier reliance on diesel among gender-diverse enterprises may be indicative of larger enterprise scales, more energy-intensive operations, or differing access conditions, particularly in off-

grid or unreliable-grid environments where diesel generators remain a dominant technology.

Electric and non-electric demand levels

Energy demand patterns across enterprises reveal important differences both by sector and by ownership structure, particularly when distinguishing between electric (including mechanical) and non-electric (thermal energy) needs, as per the methodological framework defined earlier.

Electric and mechanical energy needs are almost universal across the sample. Less than 8% of enterprises report no need for electricity or mechanical energy, and all of these are concentrated in the food sector. Among enterprises with electric and/or mechanical demands, 15% are uncertain about their exact monthly electricity consumption. Notably, awareness differed by sector: 56% of those uncertain belong to the food sector, and 44% to the textile sector.

Consumption levels further underscore sectoral differences: about 27% of enterprises consume between 1-100 kWh/month, predominantly in the food sector (75%), while 25% consume between 101-200 kWh/month, with a similar food sector dominance (67%). Meanwhile, 33% of enterprises report monthly electricity consumption exceeding 200 kWh/month, and a striking 95% of these high-demand enterprises operate within the food sector. These figures highlight the inherently higher energy intensity of food processing compared to textile production.

When analysed through the lens of ownership structure, further stratification emerges. Among sole female-owned enterprises, 95% reported electric or mechanical energy needs. However, 26% of them are unsure about their actual consumption levels. A similar pattern is observed among female-female co-owned enterprises, where 21% indicate they are unsure about their energy demand. In contrast, only 4% of gender-diverse enterprises report lacking knowledge of their electric and/or mechanical energy consumption levels. Moreover, 57% of gender-diverse enterprises consume more than 200 kWh/month, compared to just 16% of sole female-owned enterprises and 22% of female-female co-owned enterprises. This suggests that enterprises with more gender-diverse ownership structures are associated with larger operational scales or more energy-intensive production processes.

Turning to non-electric energy use, more precisely thermal energy, the patterns are markedly different. Overall, about 45% of enterprises report thermal energy

needs, but knowledge about actual thermal demand levels is generally poor. Among sole female-owned enterprises, 80% are unaware of their thermal energy consumption, compared to 70% of gender-diverse enterprises and 33% of female-female co-owned enterprises.

For those enterprises that are able to quantify thermal demand, most report relatively low consumption levels: 28% use between 1-400 kWh/month. A few outliers, all based in Kenya, report extremely high thermal demands, with one sole female-owned enterprise consuming between 1,401-1,600 kWh/month and a gender-diverse enterprise exceeding 2,000 kWh/month.

A more detailed breakdown of electric and non-electric demand levels for productive use, categorised by consumption bracket, country, and gender-based ownership structure, is presented in Appendix B.

These findings confirm that thermal energy remains a critically under-reported and under-monitored component of productive energy use in women-owned and gender-diverse MSMEs, even though it is vital for food processing and certain textile activities. The observed gaps in awareness particularly among women-only enterprises highlight an area where targeted capacity-building interventions could yield significant productivity and energy efficiency gains.

Energy expenditure per unit output

Energy expenditure patterns, measured as total monthly electricity and/or fuel costs relative to production output (USD/kg/month), further underscore critical ownership-based differences. Across the overall sample, 35% of enterprises lack sufficient data to determine their monthly energy expenditure per kilogram of output. Most of these gaps stem from the food sector (74%), while the textile sector contributes the remaining 26%.

Among enterprises with available data, 49% incur energy expenditures below or equal to 1 USD/kg/month, with a clear dominance of food sector enterprises (94%). Only a minority (8%) report expenditures between 1 and 10 USD/kg/month, largely concentrated in the textile sector (75%). Extremely high energy expenditures (above 10 USD/kg/month and even above 100 USD/kg/month) are rare but not insignificant, occurring primarily among a small subset of food sector enterprises.

Stratifying by gender-based ownership structures reveals that ownership diversity, again, correlates with enhanced data awareness, in addition to better cost efficiency. Among sole female-owned enterprises, 45% lack knowledge about their energy expenditure levels, compared to 35% among female-female co-owned and 28% among gender-diverse enterprises. Similarly, the proportion of enterprises spending less than or equal to 1 USD/kg/month increases with ownership diversity: 30% for sole female-owned, 50% for female-female co-owned, and 64% for gender-diverse enterprises.

Higher expenditures are also more common among sole female-owned businesses. Among them, 5% report paying from above 1 USD to 10 USD/kg/month, 15% spend between 10 and 100 USD/kg/month, and another 5% exceed 100 USD/kg/month. In enterprises with a female-female co-ownership structure, 10% pay above 1 up to 10 USD/kg/month, and 5% pay above 10 USD up to 100 USD/kg/month, while none of these enterprises exceed 100 USD/kg/month. In contrast, gender-diverse enterprises show a remarkable clustering below the 1 USD/kg/month threshold (92%), with only 8% paying above 1 up to 10 USD/kg/month, and none report energy expenditures above 10 USD/kg/month.

These patterns strongly suggest that enterprises with gender-diverse ownership structures may enjoy better access to energy management knowledge, more efficient technologies, or greater operational scales, thereby achieving lower energy costs relative to output. In contrast, sole female-owned enterprises appear to face greater barriers in optimising their energy use and controlling operational costs.

In summary, energy demand and expenditure patterns reveal complex but coherent associations between sector, ownership structure, and productive energy dynamics. Gender-diverse enterprises tend to operate at larger scales, utilise more diversified and complex energy portfolios, and achieve better energy cost efficiencies. Meanwhile, sole female-owned enterprises face greater information gaps, higher cost burdens, and are more reliant on fewer, often less efficient, energy sources. Addressing these disparities through targeted support in energy literacy, financing for clean technologies, and tailored energy services could constitute a critical step toward enabling a more inclusive and resilient energy transition for women entrepreneurs across Africa.

5.3.2 Findings: Gendered patterns of productive energy use in Nigerian enterprises

Building upon the cross-country assessment of women-owned enterprises presented in the previous section, this analysis turns to Nigeria as the sole focus for a more detailed gender-disaggregated comparison. Although the web-based survey initially sought to capture data from male-owned enterprises across all focus countries, Nigeria emerged as the only country where a sufficient number of responses from male-owned enterprises were obtained. Consequently, Nigeria offers a unique empirical opportunity to interrogate gendered dynamics of productive energy use across sole female-owned, sole male-owned, female-female co-owned, male-male co-owned, and gender-diverse enterprises.

Focusing on Nigerian food and textile MSMEs allows for a more fine-grained exploration of how enterprise ownership structures intersect with sectoral patterns, business formality, energy access modalities, energy demand levels, and energy expenditures. This micro-level investigation not only enriches the broader comparative framework developed earlier but also provides critical insights into the extent to which gender composition in ownership influences the productive use of energy technologies and fuels.

Following the established structure, the chapter first profiles the sample in terms of enterprise characteristics, including sectoral distribution, legal registration status, enterprise size, and ownership diversity, before moving into an analysis of energy access and use patterns. These findings set the stage for understanding how gender-related ownership dynamics manifest in tangible differences in energy behaviour, resilience, and cost-efficiency among MSMEs operating in Nigeria's food and textile sectors.

5.3.2.1 Sample overview

The gender-disaggregated sample from Nigeria comprises 46 valid MSME responses, with enterprises spanning both the food and textile sectors. However, consistent with broader regional patterns, the food sector is overwhelmingly dominant: 94% of all respondents operate within food-related ISIC classifications, including food manufacturing (74%), fishing and aquaculture (15%), and crop and animal production (4%). Only three enterprises, all owned by women, operate in the textile industry, specifically in the manufacture of wearing apparel.

Within the sample, 24% of enterprises are exclusively owned by women, while 43% are exclusively owned by men. The remaining 33% represent gender-diverse co-ownership structures. Among the women-owned enterprises, 45% are sole female ownerships and 55% are female-female co-ownerships. Similarly, among the male-owned enterprises, 65% are sole male ownerships and 35% are male-male co-ownerships. This diverse distribution of ownership structures provides a rare opportunity to systematically compare five distinct models, sole female, female-female, sole male, male-male, and gender-diverse co-ownership, within a single cross-country research framework, offering nuanced insights into gendered dynamics in enterprise operation and productive energy use.

As indicated in Table 7, gendered patterns in sectoral affiliation are particularly pronounced. Textile sector participation is limited exclusively to female-only and female-female co-owned enterprises, which together account for all three businesses in this category. Male-only, male-male, and gender-diverse enterprises are entirely absent from the textile sector, operating solely in the food sector. Within the food sector, gender-diverse and sole male-owned enterprises dominate, comprising 35% and 30% of the total, respectively. These distributions suggest that textile production remains an economic space more frequently occupied by women, whereas the food sector accommodates a broader mix of ownership models.

Table 7. Distribution of enterprises by industry sector and gender-based ownership structure in Nigeria

Industry sector	Gender-based ownership structure					Total
	Sole female	Female-female	Gender-diverse	Sole male	Male-male	
Food sector	7%	12%	35%	30%	16%	100%
Textile sector	67%	33%	0%	0%	0%	100%

Further disaggregation by ownership structure highlights nuanced variations. Among sole female enterprises, 40% are engaged in fishing and aquaculture and another 40% in the manufacture of wearing apparel, with only 20% involved in food manufacturing. In contrast, food production exhibits the highest share among

all other gender-based ownership categories: 67% of female-female co-owned enterprises, 71% of male-male co-owned enterprises, and a striking 85% and 87% of male-only and gender-diverse enterprises, respectively, are involved in food manufacturing. Engagement in fishing and aquaculture is also notable among 17% of female-female co-owners, 15% of sole male enterprise owners, and 13% of gender-diverse enterprises. Crop and animal production is exclusively undertaken by male-male co-owned enterprises, constituting 29% of this ownership group.

These patterns suggest that textile production continues to represent a predominantly female-driven economic space, while the food sector accommodates a broader and more diverse range of ownership models. They also reflect underlying gendered divisions of labour and market segmentation, reinforcing the importance of adopting disaggregated analytical lenses when investigating gender and energy dynamics in MSMEs.

Enterprise size, measured by employee count and aligned with Nigeria's national MSME definitions, also varies meaningfully by the gender in ownership. Overall, 70% of all enterprises are micro-sized, while 30% qualify as small-sized. Yet, sole female-owned enterprises exhibit the highest degree of micro-enterprise concentration, with 100% of them falling into this category. A similar tendency is observed in female-female co-owned businesses, 83% of which are micro-enterprises. In contrast, male ownership correlates with an increasing likelihood of operating at a larger scale. Among sole male-owned enterprises, 69% are micro-sized, while 31% qualify as small. This proportion shifts further among gender-diverse enterprises, with 43% small-sized. Male-male co-owned enterprises show the most balanced distribution, with 60% micro-sized and 40% small-sized, pointing to a possible association between gender-mixed ownership and greater growth capacity.

Formalisation rates are also relatively high in the Nigerian sample. Of all enterprises, 91% report being formally registered, while fewer than 7% are not registered. Only one enterprise, a sole female-owned business, declined to disclose its registration status. Within the food sector, registration stands at 93%, while in the textile sector, only 67% of enterprises are formally registered. Ownership structure again reveals important distinctions: registration rates increase with gender diversity and number of owners. Among sole female-owned enterprises, only 60% are registered, with 20% unregistered and another 20% declining to respond. Female-female co-owned enterprises display a higher registration rate of 83%, while sole male enterprises show a 92% registration rate. Enterprises with

gender-diverse or male-dominated co-ownership structures report full formal registration, indicating a potential correlation between gender diversity and male involvement in ownership and higher rates of formalisation. This pattern aligns with broader empirical findings that women-owned enterprises are more frequently concentrated in the informal sector, often due to systemic barriers in accessing finance, regulatory support, and legal infrastructure.

In sum, the Nigerian sample provides a rich empirical dataset for analysing the intersection of gender and productive energy use. Clear differences are observed across ownership structures in terms of sectoral engagement, legal formality, and enterprise size. Women-owned businesses tend to be smaller, more informal, and more likely to engage in textile-related activities, whereas enterprises with male participation, particularly gender-diverse or male-male co-owned, are generally larger, more formalised, and concentrated in the food sector. These findings set the analytical groundwork for exploring whether and how these structural patterns manifest in differentiated energy access, demand, and cost behaviours, which is addressed in the next section.

5.3.2.2 Gendered energy use patterns

Building upon the structural and sectoral characteristics outlined above, this section analyses the energy access profiles, carrier choices, consumption levels, and energy expenditures of Nigerian MSMEs across five gender-based ownership models.

Energy access and off-grid prevalence

The first distinction arises in access to grid electricity. Out of the 46 enterprises assessed, 39% operate without grid electricity and are therefore classified as off-grid. This closely mirrors Nigeria's national electricity access statistics, where approximately 40% of the Nigerian population lacks access to electricity, mirroring the distribution within the sample (while the country reports an urban electrification rate of 89% and a rural electrification rate of 26%) (The World Bank Group et al., 2023).

Yet, as previously discussed, off-grid status is not always a matter of physical isolation from infrastructure. Cross-referencing enterprise locations with the Africa Grid Database (The World Bank Group, 2017) indicates that more than half of the off-grid enterprises are located in areas with existing grid infrastructure but remain unconnected, either due to affordability constraints, bureaucratic barriers, or

perceived unreliability. Less than 17% of enterprises fall into an "uncertain access" category, where incomplete location data, recorded only at the broader state or regional level, made it impossible to conclusively determine their proximity to grid infrastructure. Meanwhile, 28% of off-grid enterprises were located in areas entirely without existing grid infrastructure.

A closer examination of the business profiles reveals that the majority of these off-grid enterprises are engaged in the manufacture of food products (78%), including rice or flour milling and palm oil production, followed by fishing and aquaculture (17%). There is also a single enterprise involved in the manufacture of wearing apparel. Typically, these enterprises rely on generators fuelled by diesel or petrol, or they use solar PV to meet their electrical and/or mechanical needs (78%). The remaining 22% address thermal demands using LPG, biomass (not further specified), and "other" unspecified energy carriers.

Disaggregating off-grid status by ownership structure reveals further nuance. Female-female co-owned enterprises exhibit the highest off-grid share (50%), followed by sole male (46%) and sole female (40%) enterprises. Enterprises with gender-diverse ownership and those co-owned by men show somewhat lower rates, at 33% and 29% respectively.

As presented in Table 8, these differences may suggest that enterprises with shared or male ownership are either more capable of navigating grid connection processes or more inclined to invest in alternative systems. Yet the relatively high off-grid presence across all ownership models points to a broader systemic issue in access to reliable grid electricity for small businesses in Nigeria.

Table 8. Characteristics of off-grid operating enterprises in Nigeria

Country	Location	Energy carrier	ISIC category	Business activity	Gender-based ownership structure	Existing grid line
Nigeria	Abeokuta, Ogun State	LPG, Other	3	Fish drying	Female-female	Yes
Nigeria	Ijebu Ode, Ogun State	Petrol, LPG	3	Fishing and rearing	Gender-diverse	Yes

Nigeria	Ibogun Olaogun, Ogun State	Diesel	10	Palm oil production	Gender-diverse	Yes
Nigeria	Lafia, Nasarawa State	Diesel, Other	10	Rice milling	Gender-diverse	Yes
Nigeria	Abeokuta, Ogun State	Diesel, Solar PV, Other	10	Palm oil production	Gender-diverse	Yes
Nigeria	Ogbomosho, Oyo State	Diesel	10	Rice milling	Female-female	No
Nigeria	Ogun State	Diesel	10	Rice milling	Gender-diverse	Uncertain
Nigeria	Ota, Ogun State	Biomass, Other	3	Fish drying	Sole female	Yes
Nigeria	Borno State	Solar PV	14	Flour milling and fish drying	Sole female	Uncertain
Nigeria	Yola North, Adamawa State	Biomass	10	N/A	Female-female	Yes
Nigeria	Odeda, Ogun State	Diesel, Solar PV	10	Palm oil production	Sole male	Uncertain
Nigeria	Ijebu Igbo, Ogun State	Diesel	10	Rice milling	Sole male	Yes
Nigeria	Wukari, Taraba State	Diesel, other	10	Rice milling	Sole male	No

Nigeria	Iresaadu town, Oyo State	Diesel	10	Rice milling	Male-male	No
Nigeria	Iwere-Ile, Oyo State	Diesel	10	Rice milling	Sole male	No
Nigeria	Abeokuta, Ogun State	Diesel	10	Rice milling	Sole male	Yes
Nigeria	Oke-irun, Osun State	Diesel	10	Rice milling	Sole male	No
Nigeria	Kura, Kano State	Diesel	10	Rice milling	Male-male	Yes

Energy carrier diversity

Turning to the number and composition of energy carriers used, a pattern of moderate diversification is observed. Across the sample, 46% of enterprises use two distinct energy carriers, most commonly a combination of grid electricity and fuel. Another 28% engage three or more carriers, while 26% rely on a single energy source. In the food sector, which comprises the vast majority of enterprises, nearly half use two carriers and 30% use three or more, reflecting the complex energy service needs of food processing activities. In contrast, textile enterprises, all of which are women-owned, rely exclusively on a single energy source, either grid electricity or solar PV.

Gender-based ownership structures correlate strongly with energy carrier diversification. Sole female and female-female co-owned enterprises are more likely to depend on just one or two energy carriers (80-83%), while 29-31% of sole male and male-male co-owned enterprises use three or more. Notably, gender-diverse enterprises exhibit the highest share of three-plus carrier usage (33%), suggesting that gender-diverse enterprises as well as those with at least one male owner, may have greater capacity or inclination to integrate hybrid energy systems. This may be indicative of broader trends in technological adoption, managerial diversity, or financing access. A more detailed breakdown of energy carrier use by gender-based ownership structure for Nigeria can be found in Appendix B.

The predominant combination across ownership models remains grid electricity and fuel, used by 40% of sole female enterprises, 46% of sole male enterprises, 53% of gender-diverse businesses, and 57% of male-male co-owned enterprises. In contrast, female-female co-owned businesses show a distinctive pattern: only 17% use this combination, while 50% rely exclusively on fuel, indicating a lower level of electrification or a stronger dependence on autonomous generation technologies. Solar PV, while still relatively limited, is integrated into the energy mix by a small number of enterprises across all ownership models, most commonly in combination with either fuel or grid electricity.

Fuel use, which is only observed in the food sector and represents a critical indicator of both operational scale and sustainability, further illustrates gendered divergence. Diesel remains the dominant fuel across all enterprises using fuel, reported by 70% of the relevant sample. Biomass follows at 26%, petrol at 23%, and LPG at 16%. Patterns shift meaningfully by ownership model. Sole female-owned enterprises show the highest reliance on biomass (40%), with declining use across female-female (33%) and gender-diverse enterprises (17%). In contrast, diesel use increases with gender diversity and male ownership: from 50% among female-female co-owners to 73% among gender-diverse partnerships and 77% among sole male businesses, and up to 86% among male-male co-owners. Petrol is used by approximately 20-29% of enterprises across most ownership structures, with the notable exception of female-female co-owned businesses, where no use of petrol is reported. In contrast, LPG usage is most prevalent among female-female co-owned enterprises, reaching 33%.

These distinctions reflect multiple overlapping drivers: technological preferences, cost constraints, access to fuels, and operational scale. Diesel use is more prevalent in larger enterprises and in off-grid contexts, where generators often represent the default backup or primary energy source. Biomass, on the other hand, is often used for thermal needs in smaller-scale food production. The preference for cleaner fuels like LPG is highest among female-female co-owned enterprises (33%), with markedly lower use among gender-diverse (7%) and male-male owned businesses (0%).

Electric and non-electric demand levels

A sectoral analysis of energy demand levels across the Nigerian sample reveals both commonalities and significant divergences between ownership structures. Electrification for productive use is near-universal: only 7% of enterprises,

exclusively from the food sector, reported having no electric or mechanical energy needs. In contrast, the absence of thermal energy needs is far more pronounced: around 61% of all enterprises do not require thermal energy for their productive activities. Within this subsample, 11% are textile businesses (which are not typically thermal energy-intensive), while the remaining 89% originate from the food sector, where thermal processes such as drying, boiling, and milling are common.

Among enterprises with electric and/or mechanical demand, energy awareness is high: not a single respondent indicated uncertainty about their electricity consumption levels. Yet notable differences emerge when examining the magnitude of consumption. Approximately 16% of enterprises consume between 1-100 kWh/month, a bracket overwhelmingly dominated by food enterprises (88%), with textile enterprises representing the remaining 12%. A further 30% report consumption levels between 101-200 kWh/month, again with the food sector comprising 85% of these enterprises. Most strikingly, a majority (54%) of the sample reports monthly electric and/or mechanical energy demand exceeding 200 kWh/month, all of which are concentrated within the food sector, underscoring the energy-intensive nature of food processing activities compared to textile manufacturing.

Disaggregating by gender-based ownership structures, clear patterns emerge. Electric and/or mechanical energy demands are almost universal across ownership models, ranging from 77% among female-female co-owned enterprises, to 80% in sole female-owned businesses, up to 100% among sole male and gender-diverse enterprises, as well as male-male co-owned enterprises. Additionally, the intensity of electric demand correlates with the gender composition of ownership. Enterprises exceeding 200 kWh/month are absent among sole female-owned businesses, only present in 33% of female-female co-owned businesses, and rise to 38% among sole male-owned, 67% among gender-diverse, and 86% among male-male co-owned enterprises. Conversely, lower electric demand levels (1-100 kWh/month) are more commonly observed among sole female-owned and female-female co-owned enterprises, while none of the male-male co-owned enterprises fall into this lower consumption bracket.

Thermal energy use exhibits even sharper gendered contrasts. Overall, 27-50% of enterprises in each ownership category report some level of thermal energy needs. Gender-diverse enterprises are least likely to rely on thermal energy (73% reported no thermal needs), followed by sole female-owned businesses (60%). In

contrast, 54-57% of enterprises owned entirely by men (either solely or in male-male partnerships) do not rely on thermal energy carriers.

Awareness of thermal energy consumption levels remains limited. Among sole female-owned enterprises, 40% are unaware of their thermal energy consumption, followed by 29% of male-male co-owned enterprises, and around 15-20% across other ownership types. Thermal energy demand above 400 kWh/month is found exclusively among male-owned enterprises. Specifically, 14% of male-male co-owned enterprises consume between 401-800 kWh/month, while 23% of sole male-owned businesses consume above 800 kWh/month. By contrast, among enterprises with at least one woman in the ownership structure, thermal energy needs remain relatively modest: 33% of female-female and 7% of gender-diverse businesses report thermal energy consumption levels between 1-400 kWh/month.

A more detailed breakdown of electric and non-electric demand levels for productive use, categorised by consumption bracket and gender-based ownership structure from the Nigerian sample, is presented in Appendix B.

In essence, gender-diverse and male-owned enterprises tend to exhibit higher total energy demand, particularly for electric and mechanical operations, while sole female-owned enterprises show lower energy demand levels but also greater gaps in energy awareness, especially regarding thermal needs.

Energy expenditure per unit output

The assessment of monthly energy expenditures, combining both electricity and fuel costs relative to production output (expressed in USD/kg/month), offers further insight into operational efficiency across ownership structures.

Across the full Nigerian sample, 37% of enterprises lack available data on monthly energy costs. The reasons for this gap appear twofold: some entrepreneurs are unfamiliar with the costs associated with their energy carriers, while others did not report production output values necessary for normalising expenditure. 94% of enterprises without energy expenditure data belong to the food sector, with only a minor 6% from the textile sector.

Among the enterprises that provided cost data, 59% report energy expenditures less than or equal to 1 USD/kg/month, strongly dominated by food sector businesses (96%). Only one enterprise in the food sector recorded an expenditure slightly above 1 USD/kg/month (specifically, 1.29 USD/kg/month), while one enterprise in

the textile sector reported energy costs exceeding 10 USD/kg/month (10.07 USD/kg/month).

When dissecting energy expenditure patterns by ownership structure, a compelling correlation emerges between gender dynamics and cost management. Sole female-owned enterprises exhibit the highest rate of missing cost data, with 80% unable to report their monthly energy expenditures. Sole male and male-male co-owned enterprises follow, with 46% and 43% of respondents, respectively, lacking this information. In contrast, co-owned enterprises involving women (both female-female partnerships and gender-diverse enterprises) demonstrate much higher awareness, with only 20% and 17% respectively failing to report expenditure data.

For enterprises that did report, co-ownership structures, especially those involving women, display notable cost advantages. Approximately two-thirds of female-female co-owned and gender-diverse enterprises report energy costs below 0.1 USD/kg/month. Male-male co-owned enterprises also perform relatively well, with 46% reporting expenditures within the lowest cost bracket. Higher expenditures, conversely, are more common among sole proprietorships: one sole female-owned enterprise exceeds 10 USD/kg/month, while one sole male-owned enterprise reported slightly above 1 USD/kg/month.

A similar trend is observed in enterprises paying between 0.1 and 1 USD/kg/month: 17% of female-female co-owned, 13% of gender-diverse enterprises, and 14% of male-male co-owned businesses fall into this bracket. These figures suggest that shared enterprise ownerships, particularly those including at least one female, are associated not only with improved awareness of energy costs but also with lower energy expenditures relative to output. Thus, the findings imply that enterprise structures characterised by diversity, whether through co-ownership or gender balance, may be better positioned to optimise energy use, manage operational costs, and potentially achieve higher productivity levels.

In summary, the analysis of Nigerian MSMEs reveals pronounced differences in productive energy use across gender-based ownership structures. Gender-diverse and male-male co-owned enterprises tend to operate at larger scales, exhibit higher levels of electric and thermal energy demand, and more frequently integrate multiple energy carriers. These enterprises also report lower unit energy costs and higher awareness of energy expenditure, suggesting greater operational efficiency and more robust energy management practices. By contrast, sole female-owned

enterprises are more likely to remain micro-scale, rely on biomass and LPG, and report the lowest levels of thermal energy awareness. They also exhibit the highest incidence of missing data on energy expenditure, limiting their ability to track or manage production efficiency. Female-female co-owned businesses occupy an intermediate position, showing higher rates of formal registration than sole female-owned enterprises and a greater tendency to adopt cleaner fuels, but also displaying limited energy diversification and a greater dependence on fuel-only systems.

Taken together, these findings suggest that gender composition in enterprise ownership is not only correlated with sectoral orientation and formality but also shapes energy access modalities, consumption profiles, and cost-efficiency. While ownership diversity appears to support more sophisticated energy strategies and lower operational costs, women-owned enterprises, especially those without male co-owners, continue to face systemic constraints that may limit their ability to benefit from energy transitions. These differentiated patterns point to the need for gender-sensitive support mechanisms that address both the structural barriers to formality and scale, as well as the technical and financial gaps in productive energy use.

5.4 Discussion

At the centre of this part of the research lies a core question: ***to what extent does the gender composition of enterprise ownership influence productive energy use in MSMEs?*** Addressing this question is crucial not only for understanding differentiated energy use patterns across African MSMEs but also for designing energy access interventions that are inclusive, equitable, and attuned to the varying capacities and constraints of entrepreneurs, particularly women operating in marginalised economic contexts (Pueyo, Carreras, et al., 2020).

To investigate this question, the study employed a descriptive cross-sectional research design, supported by analytical comparisons across gender-based ownership categories (Aggarwal & Ranganathan, 2019; Siedlecki, 2020). This approach allowed for mapping of patterns in ownership structure, enterprise size, energy carrier use, energy demand, and cost efficiency across two tiers of analysis: a cross-country sample of women-owned MSMEs in seven African countries and a nationally focused comparison of male- and female-owned enterprises in Nigeria. While such a design is particularly well-suited for exploratory, observational work, it also imposes clear limitations. First, the absence of statistical testing restricts the interpretive scope: relationships between gender and energy use could be observed

and compared but not generalised or causally inferred. Second, the reliance on self-reported, web-based data constrained the granularity of technical and financial information, particularly in thermal energy use and cost estimation. Third, the descriptive focus limits control over potential confounding variables, such as rurality, education level, or sector-specific constraints, factors that future studies with more robust statistical models could explicitly examine.

However, these limitations do not necessarily constitute methodological deficiencies. Rather, they reflect the broader state of knowledge and practice in productive use research, where gendered enterprise data remain sparse, and where descriptive insights still play a crucial role in framing more targeted inquiry. As Andrews et al. (2003) and Regmi et al. (2016) note, web-based surveys, when properly designed and transparently analysed, can yield important empirical baselines in contexts where in-person research remains logistically or financially constrained. Moreover, the research contributes methodologically by moving beyond the conventional binary framing of "female" versus "male" enterprise ownership. Instead, it distinguishes five ownership structures: sole female, female-female, gender-diverse, sole male, and male-male, a level of granularity rarely achieved in productive use energy studies.

Drawing from this unique dataset, the discussion now turns to key dimensions in which ownership structure seems to interact with productive energy use: electricity access, expenditure, energy carrier diversity, and demand levels.

First, electricity access patterns reveal both structural barriers and differentiated enterprise responses shaped by ownership configuration, with consequential effects on cost-efficiency. Across both tiers of the study, a significant proportion of enterprises, 25% in the cross-country sample and 39% in Nigeria, operated off-grid. However, the implications of off-grid status diverged meaningfully depending on context and ownership structure.

Within the cross-country sample, gender-diverse enterprises were disproportionately represented among off-grid businesses, while in the Nigerian sub-sample, this pattern was most pronounced among female-female co-owned enterprises. Notably, many of these enterprises were situated in areas with existing grid infrastructure, underscoring that physical proximity to the grid does not necessarily translate into meaningful energy access. Therefore, their off-grid status could be less indicative of exclusion and potentially more of strategic autonomy, likely driven by grid unreliability, bureaucratic hurdles, or prohibitive connection

fees (Bhatia & Angelou, 2015; The World Bank Group et al., 2023). These enterprises frequently adopted decentralised solutions such as solar PV or hybrid systems, choices that signal stronger planning capacity, better access to finance, and greater organisational agility. Crucially, they also reported some of the lowest unit energy expenditures, suggesting that off-grid operation, when coupled with diverse ownership, can yield tangible cost advantages (V. Hunt et al., 2015). For instance, in Nigeria, two-thirds of gender-diverse and female-female enterprises reported energy costs below 0.1 USD/kg/month, a level of efficiency rarely observed among sole proprietors. In contrast, sole female-owned enterprises not only recorded the highest incidence of missing expenditure data, but also the highest per-unit energy costs where data were available. This pattern suggests that ownership diversity could shape the underlying financial governance of energy use. These findings align with existing evidence linking enterprise diversity to improved performance, not just through access to capital or labour, but via enhanced decision-making, collaborative oversight, and resource optimisation (V. Hunt et al., 2015). Sole female proprietors, often navigating micro-sized enterprises and operating predominantly informally (Rojas et al., 2012; SME Finance Forum, 2023) as observed in this study, tend to struggle with limited support, face intersecting barriers in both energy access and financial planning, barriers that could translate into higher operational costs and reduced competitiveness (De Groot et al., 2017; Dutta et al., 2017; Edomah et al., 2021; Ferroukhi, Renner, et al., 2019; Pueyo & Maestre, 2019). Moreover, the fact that these enterprises also showed the lowest awareness of thermal demand and expenditure highlights a critical data and knowledge gap.

These findings align with a growing body of literature that highlights decentralised, autonomous energy systems as often more viable and context-appropriate solutions for MSMEs, particularly in settings where grid reliability, affordability, or accessibility remains limited (Dibaba et al., 2023; Falchetta et al., 2022). For enterprises with the governance capacity to manage decentralised energy systems, particularly those with team-based or gender-diverse ownership structures, off-grid solutions may offer not only autonomy but also cost efficiency. Conversely, grid reliance without the capacity to optimise usage or monitor expenditure can lock smaller, sole-owned businesses into suboptimal energy-cost ratios.

Second, patterns of energy carrier usage reveal significant ownership-related variations in technology adoption and the resilience of energy systems. Across both datasets, sole female-owned and female-female co-owned enterprises reported fewer energy carriers, typically one or two, and were more reliant on grid electricity

or thermal fuels such as LPG or biomass. In contrast, gender-diverse, sole male, and male-male co-owned enterprises showed greater energy diversification, including more frequent use of solar PV and hybrid combinations of grid electricity, fuel, and decentralised sources. Notably, gender-diverse enterprises in both samples reported the highest incidence of three or more energy carriers, indicating greater operational flexibility and likely access to capital or technical capacity to manage more complex energy systems. This aligns with prior research showing that diverse leadership structures can enhance adaptive decision-making (V. Hunt et al., 2015), potentially facilitating the uptake of innovative energy solutions.

Third, electric and non-electric energy consumption demonstrates linkages to ownership stratification. In both the cross-country and Nigeria datasets, enterprises with male or gender-diverse ownership were more likely to exceed 200 kWh/month in electric or mechanical demand, particularly in food manufacturing, which is typically more energy-intensive than textile production. Sole female-owned and female-female enterprises, in contrast, tended to report lower consumption levels. While this may reflect genuine differences in scale or technology intensity, it may also point to constraints in energy literacy or access to high-efficiency equipment (Pueyo, Bawakyillenuo, et al., 2020). Thermal energy demand further magnifies this gap. Not only was thermal demand significantly under-reported in the cross-country sample, but awareness of actual thermal usage was lowest among sole female-owned businesses in both datasets. This suggests a deeper structural invisibility: when thermal energy is not adequately measured or conceptualised within enterprise planning, it remains excluded from both data and policy frameworks. As Pueyo & Maestre (2019) argue, productive use strategies have historically prioritised electricity, sidelining critical thermal needs that underpin food drying, boiling, and other heat-intensive processes. The lack of thermal demand awareness may therefore be both a cause and a consequence of policy neglect.

Table 9 provides a high-level, simplified synthesis of the observed patterns across enterprise ownership structures from both samples, capturing how different configurations of ownership shape energy access modalities, the range and complexity of energy sources used, and the extent to which enterprises are aware of and manage their energy needs and costs.

Table 9. Comparative summary of energy access and use characteristics by enterprise ownership structure across cross-country and Nigerian samples

	Cross-country sample				
	Nigeria sample				
	sole female	female-female	gender-diverse	sole male	male-male
Off-grid operations	low	low	medium		
	medium	medium	low	medium	low
Energy carrier diversity	1-2	1-2	≥2		
	1-2	1-2	≥3	≥3	≥3
Type of fuel used	LPG, NG, biomass	LPG, biomass, diesel	diesel, biomass		
	biomass, petrol	diesel, biomass, LPG	diesel, petrol	diesel, petrol	diesel, petrol
Awareness of energy consumption level	low to medium	medium to high	medium to high		
	medium	medium to high	high	high	high
Energy consumption level	low	low	high		
	low	medium	high	medium	high
Awareness of energy expenditure	low	medium	high		
	low	high	high	medium	medium

Energy expenditure per unit output	high	low to medium	low		
	medium to high	low	low	medium to high	low to medium

In sum, these findings offer new empirical insight into how enterprise ownership structure, not just gender per se, shapes the energy access and use landscape in African MSMEs. The results align with and extend recent evidence that calls for more intersectional, ownership-sensitive energy access policies (Clancy & Dutta, 2005; Pueyo et al., 2019; Pueyo & Maestre, 2019). They also reinforce the importance of addressing the thermal energy blind spot and improving energy literacy, particularly among micro-enterprises and sole proprietors.

Yet the study also leaves critical questions open. Without deeper qualitative insights into how ownership dynamics shape decision-making, about grid connection, fuel choice, or expenditure trade-offs, the relational patterns observed here remain only partially understood.

Looking ahead, three priorities emerge. First, productive use programmes must integrate thermal energy into their diagnostic and planning tools, not just electricity, and tailor support toward underrepresented segments such as sole female entrepreneurs. Second, energy finance mechanisms should reflect enterprise diversity, offering tailored support to sole proprietors and co-owned ventures alike, whether through differentiated loan terms, bundled training, or simplified hybrid energy solutions (Dibaba et al., 2023; Falchetta et al., 2022). Third, future research could triangulate survey findings with in-person audits, semi-structured interviews, and gender-sensitive value chain analysis to better understand the interplay between enterprise ownership, decision-making, and energy performance.

5.5 Conclusions

This chapter has interrogated how the gender composition of enterprise ownership influences the patterns, scale, and efficiency of productive energy use among MSMEs in Africa. By moving beyond the typical binary of “women-” versus “men-owned” enterprises, the study’s five-category ownership typology enabled a more differentiated understanding of gendered enterprise dynamics, an approach rarely applied in productive use research. In doing so, it revealed

ownership structure as a significant factor impacting access to energy, technology adoption, and cost performance.

Critically, the findings highlight that enterprises owned by a sole female entrepreneur face persistent disadvantages, including limited energy diversification, reduced demand scale, and high per-unit energy costs. Yet, this is not simply a function of infrastructure constraints or firm size. Rather, it reflects systemic differences in decision-making capacity, access to finance, and energy literacy, differences that are often rendered invisible when ownership is treated as a homogeneous category. The consistent under-reporting of thermal energy demand across contexts, particularly among women-owned enterprises, further illustrates how structural knowledge gaps translate into analytical and programmatic blind spots.

While the descriptive cross-sectional design offered a valuable entry point for comparative analysis, its limitations must be acknowledged. The absence of statistical controls, the reliance on self-reported data, and the remote nature of the survey constrained the granularity and reliability of key indicators. Nevertheless, the study's value lies precisely in revealing these gaps, not only as limitations of method, but as manifestations of the very capacity deficits and information asymmetries that constrain MSME performance and energy inclusion across the continent.

Building on this analytical foundation, the next chapter shifts from comparative survey analysis to in-depth case study investigation. Through on-site enterprise visits and energy audits, it explores how women entrepreneurs navigate the practical realities of accessing, using, and adapting energy systems in their day-to-day operations. By grounding the findings in lived experience, the following chapter deepens the empirical and theoretical contributions of this study, moving from patterns to processes, and from correlation to explanation.

Chapter 6

6. Productive use in women-owned enterprises – At what level do women entrepreneurs access energy, and which energy services are required?

6.1 Introduction

While the Nigerian sample in the previous chapter enabled a gender-disaggregated comparison across different ownership structures, the present phase of the research focuses exclusively on women-owned and co-owned enterprises. The limited availability of male-owned enterprise interviews across other countries made a robust multi-country gender comparison infeasible for this phase, which is why the analysis was intentionally narrowed to this subset of enterprises.

Much of the existing literature on gender and energy access continues to centre on the household level, with limited attention given to women as productive energy users (Feenstra & Özerol, 2021; Pueyo & Maestre, 2019). Yet, as women increasingly engage in entrepreneurial activities, their energy needs extend well beyond lighting and cooking. Women entrepreneurs operate in environments where unreliable, unaffordable, and inefficient energy systems not only constrain productivity but also reinforce structural inequalities in the labour market and value chain participation (Asibey et al., 2021; ENERGIA et al., 2022; Muza & Thomas, 2022; Pueyo & Maestre, 2019). Despite this, empirical data on the energy services required by these enterprises, such as appliance load, fuel diversity, temperature requirements, and cost burdens, remain sparse (ENERGIA et al., 2022; Patnaik et al., 2021). In most cases, energy demand curves are extrapolated from household

data, missing enterprise-specific drivers and masking women's productive contributions (Chandrasekaran et al., 2023; Few et al., 2022).

This study addresses this gap by collecting enterprise-level data through semi-structured face-to-face interviews with women entrepreneurs across Northern, Western, and Eastern Africa. Two central research questions guide this chapter: (1) ***what are the key characteristics of energy access for productive use among women entrepreneurs?*** And (2) ***what barriers and drivers influence women entrepreneurs' adoption of renewable energy technologies?***

Drawing on a structured interview tool aligned with the MTF methodology, the analysis quantifies access tiers while qualitatively capturing the experiences, aspirations, and constraints shaping women's energy choices. This dual approach not only identifies gaps in access but also contextualises them within the broader social and institutional landscapes that shape women's enterprise development. Furthermore, the study captures the entrepreneurs' expressed preferences and investment willingness for renewable energy solutions, offering insights into the design of gender-responsive energy interventions.

6.2 Materials and methods

Consistent with the study's overarching focus, this research phase is limited to women-owned and co-owned enterprises. This allows for a more targeted investigation into gender-specific energy access dynamics, following the broader comparative framing introduced in Chapter 5.

The methodological design of this part of the research study adopts a mixed-methods approach, integrating quantitative measurement with qualitative exploration. This choice reflects the recognition that women's energy access experiences are inherently multidimensional, shaped not only by technical metrics but also by social, cultural, and institutional dynamics. Relying solely on numeric indicators risks overlooking these nuances. Accordingly, the combination of structured data collection with narrative insight enables a more comprehensive analysis, an approach increasingly recognised as best practice in gender and energy research (Pueyo, Bawakyillenuo, et al., 2020; Pueyo, Carreras, et al., 2020; Wiese, 2020). A concurrent design was adopted to collect and analyse data in parallel, enabling simultaneous triangulation and reinforcing the validity of findings (Peterson Combs & Onwuegbuzie, 2010; Schoonenboom & Johnson, 2017). While the quantitative component was dominant, structured around the MTF tiers, the

qualitative data provided essential nuance, particularly in relation to barriers and drivers of renewable energy uptake.

The overall approach to data collection and analysis is summarised in Figure 11 and is further detailed in the subsequent sections.

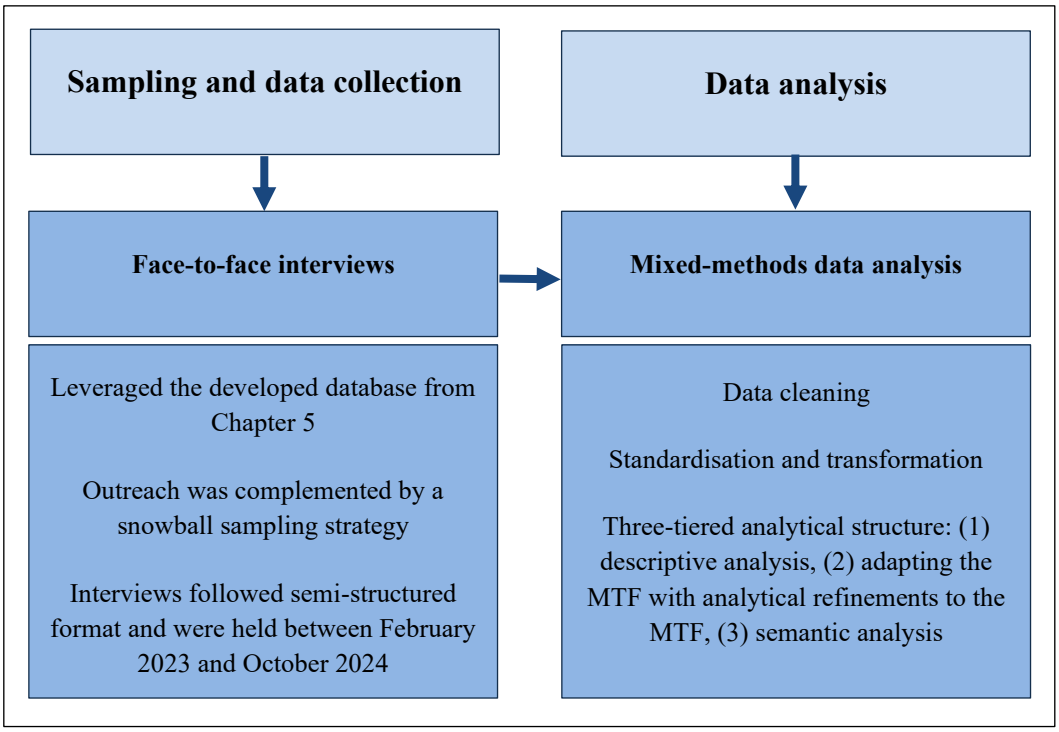

Figure 11. Overview of sampling and data collection, as well as data analysis used for the face-to-face interviews

The research design remains observational and non-experimental. It does not attempt to identify causality but rather to uncover relationships between energy access characteristics and enterprise performance, as perceived and reported by the women entrepreneurs themselves. The goal was not to generalise statistically but to provide transferable insights grounded in empirical diversity.

6.2.1 Sampling and data collection

This chapter builds on the foundation established in Chapter 5, where an extensive outreach campaign led to the creation of a database comprising around 200 women-owned MSMEs across seven African countries. That database, developed in collaboration with NGOs, academic institutions, public agencies,

development partners, and private sector actors, served as the sampling frame for the second phase of data collection focused on qualitative depth.

All enterprises from the original database were contacted and assessed against the pre-established eligibility criteria: (1) active engagement in either the food or textile sector as defined by ISIC, (2) use of at least one energy carrier for productive purposes, and (3) the presence of at least one female in the enterprise's ownership structure. Only enterprises fulfilling all three criteria were retained for further consideration.

In addition to direct outreach, a snowball sampling strategy was employed to expand the pool through referrals, where one entrepreneur could recommend another eligible participant within their professional or social network. Each referred case was individually assessed for eligibility. The final selection was based on feasibility criteria, including accessibility and logistical constraints. While efforts were made to include a diversity of regions within each country, most interviews were ultimately conducted in or near capital cities or major economic centres, where MSME concentration and infrastructure access are typically highest. This process resulted in a final sample of 40 micro- and small-sized women-owned enterprises, nearly evenly split between the food and textile sectors.

While modest in number, this sample size is consistent with comparable studies in complex, multi-country research on gender and energy (Ceschin et al., 2023; Jreich, 2024; Wiese, 2020). The decision to limit the sample was intentional: the study privileges qualitative depth and contextual diversity over representativeness, with each case offering a granular lens on enterprise-level energy access realities.

The inclusion of Egypt, despite yielding only one qualifying case in this research phase, was retained for strategic and analytical reasons. Egypt represents a contrasting policy and infrastructure landscape within the African context. As a North African country with more advanced energy infrastructure but distinct patterns of gender dynamics in enterprise ownership and visibility, Egypt serves as a valuable counterpoint within the broader African context.

Interviews were conducted face-to-face by the researcher between February 2023 and October 2024. Prior to each session, participants were informed about the study's purpose, their voluntary participation, and their right to anonymity. Verbal informed consent was obtained in accordance with research ethics protocols, and all data were anonymised to protect participant identity.

The interviews followed a semi-structured format and were guided by a pre-designed questionnaire that included both closed and open-ended questions. The instrument was developed following the Interview Protocol Refinement Framework (Castillo-Montoya, 2016), incorporating three of its four phases: aligning interview questions with the overarching research aims, structuring inquiry-based dialogue, and revising the instrument through expert feedback. Due to time constraints, the pilot-testing phase was not conducted. Nevertheless, the interview design remained adaptable throughout the process, allowing participants to elaborate on topics beyond the initial scope. Each interview lasted approximately 60 minutes, with some extended depending on participant availability and willingness to share further details (Kothari, 2004; Taherdoost, 2022).

Responses were recorded using structured, paper-based templates that facilitated the simultaneous documentation of standardised variables and open-ended qualitative insights. Where participants provided consent, audio recordings were used in parallel to supplement written notes. Question transitions were facilitated using connective language, and prompts such as "Can you tell me more about that?" were used to deepen engagement. Interviews concluded with an open-ended question inviting any final thoughts or additions.

As illustrated in Figure 12, the questionnaire comprised three core thematic areas. The first focused on socio-economic characteristics, including business activity, location, formalisation status, enterprise size, ownership composition, and demographic information about the entrepreneur. The second assessed energy access and utilisation, including types and combinations of energy carriers, energy consumption levels, reliability, appliances used, and associated costs. The third explored the potential for renewable energy adoption, capturing attitudes, perceived barriers and drivers, investment preferences, and willingness to pay[5].

[5] Other willingness to pay elicitation techniques employ more sophisticated methods to determine a precise price point. However, given that this was not the central focus and in light of time constraints during field interviews, participants were instead asked to provide a direct personal estimation of their willingness to pay.

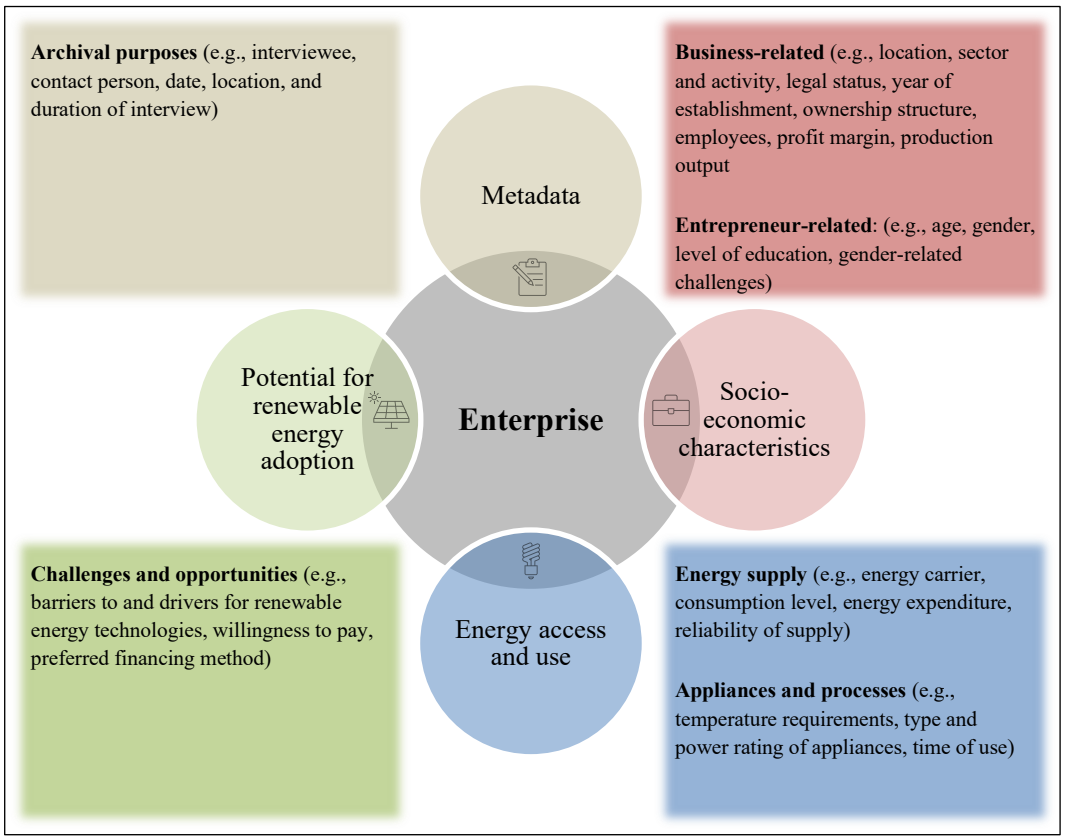

Figure 12. Questionnaire structure

Standard metadata was also collected for internal archival and categorisation purposes. The full questionnaire is available in Appendix C. All raw and processed data from the interviews are securely archived and accessible through the Mendeley Data repository (Gad & Leone, 2025).

6.2.2 Data analysis

Building on the sampling and data collection strategy outlined above, this section details the analytical framework employed to interpret the interview data collected from women-owned and co-owned enterprises across seven African countries. A three-tiered analytical structure was chosen, implemented within a concurrent mixed-methods design, allowing both quantitative and qualitative data to be collected and analysed in parallel. This enabled simultaneous triangulation of findings and a more layered understanding of the energy realities facing women entrepreneurs (Schoonenboom & Johnson, 2017). The analysis followed a systematic progression: beginning with data reduction and display, then applying

comparative and interpretive techniques to derive empirical insights (Peterson Combs & Onwuegbuzie, 2010).

The three-layered analytical structure started with a descriptive analysis to map the sample's socio-economic and energy characteristics, including sectoral activity, appliance use, and dominant energy carriers. This provided a contextual foundation, allowing for cross-case comparison and a better understanding of baseline operational profiles.

Second, the MTF was applied to measure the level and quality of energy access across eight service attributes, enabling structured benchmarking of energy adequacy at the enterprise level. The decision to apply the MTF in this context is supported by its growing prominence in international energy access monitoring and planning. Originally developed by the World Bank to improve granularity in SDG 7 tracking, the MTF has since been incorporated into open-source tools such as OnSSET and Optimus (Optimus, 2024; The World Bank Group et al., 2023). While the framework was designed primarily for household or community energy use (Elmorshedy et al., 2021; Tonolo et al., 2023), recent literature highlights its adaptability for productive use contexts, including clean cooking, mini-grids, and enterprise energy transitions (Ossei-Bremang et al., 2023; Tomei et al., 2020; Wu et al., 2024). Despite this utility, the framework is not without limitations. Scholars have critiqued its data intensity, narrow treatment of backup systems, and difficulty in capturing informal or hybrid energy arrangements common in African MSMEs (Groh et al., 2016). Nonetheless, the tiered system provides a structured lens through which to assess energy deficits, and when combined with qualitative insights, can offer a more holistic understanding of energy access challenges among women entrepreneurs. That is why, in addition to the core MTF application, several targeted analytical refinements were introduced to deepen the explanatory value of the framework and better illuminate the energy realities of women-owned and co-owned enterprises.

These refinements extended the framework across four complementary axes, linking energy access to financial, operational, and behavioural dimensions. First, enterprises performing at the lower end of the access spectrum were examined more closely by contextualising their reliability and availability scores against national-level benchmarks using World Bank data, which offers a more systemic view of infrastructural constraints. Second, to expand the affordability analysis, the study went beyond the MTF's tariff-based thresholds to assess actual energy expenditures relative to total business costs and revenues. Third, the relationship between energy

costs and enterprise viability was further explored by comparing energy expenditure intensity with self-reported profit margins, highlighting patterns in cost-performance dynamics. Lastly, willingness to invest in renewable energy or pay for improved energy services was assessed as a behavioural indicator of transition readiness, including preferences for specific financing models (e.g., instalments, grants, or one-time payments) aligned with current payment behaviours. Together, these extensions situate the MTF in a broader diagnostic framework that recognises both the technical and contextual dimensions of energy access.

Third, and as a final step of the overall three-layered analytical structure, to complement and contextualise these findings, semantic content analysis was conducted on open-ended interview responses. This qualitative strand explored gendered business constraints, barriers to renewable energy uptake, and perceived drivers for energy transitions, yielding insight into lived realities and subjective investment preferences.

The overall data analysis framework is summarised in Figure 13.

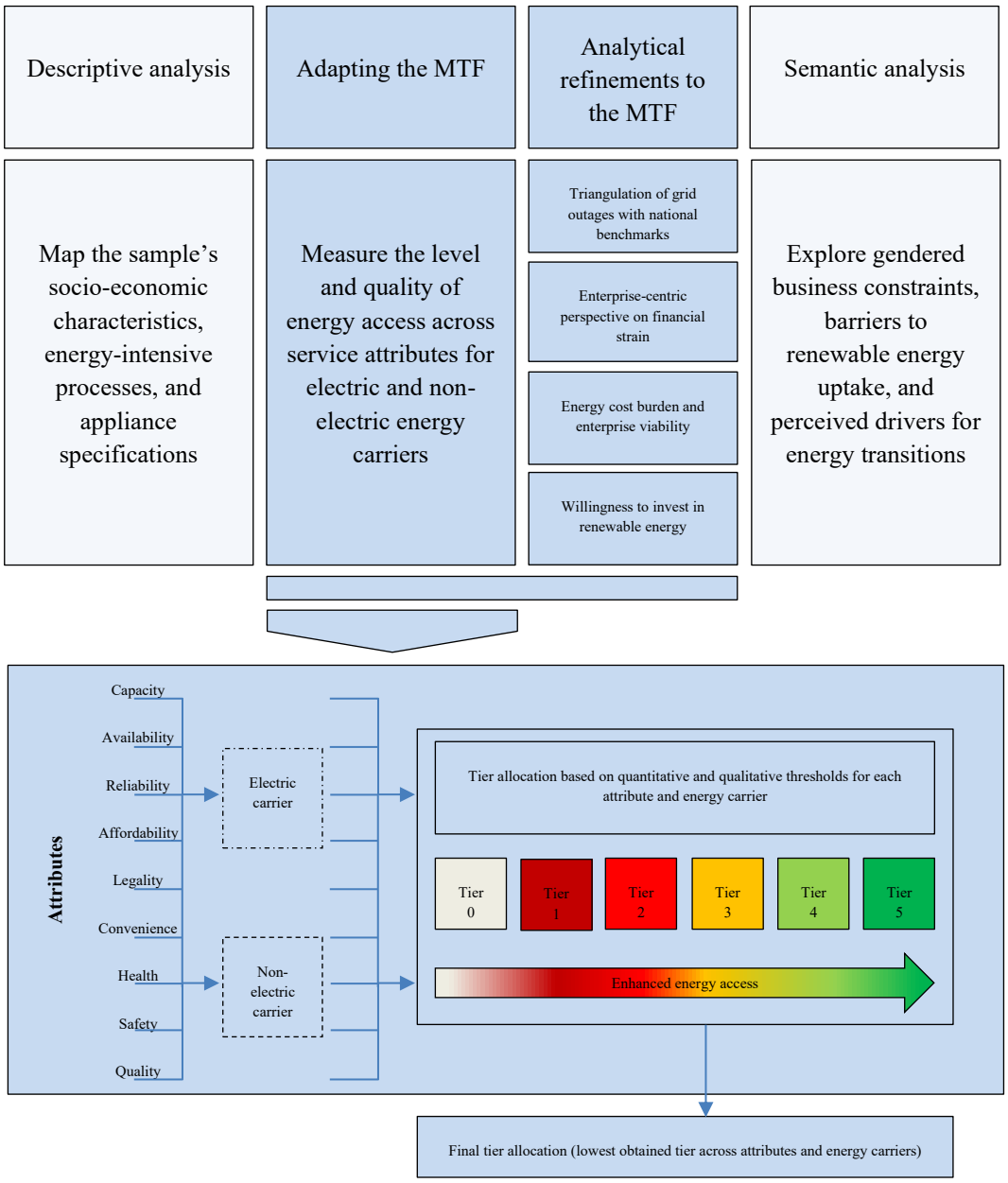

Figure 13. Three-layered analytical framework for assessing energy access and contextual constraints in women-owned enterprises

Notes: This table presents the quality attribute from the MTF for illustrative purposes only. Due to data limitations, this attribute was not included in the formal analysis.

This layered approach was chosen to respond to critical gaps identified in the literature, where purely technical metrics often miss the social and institutional contexts that shape energy access and use among women entrepreneurs (Clancy & Dutta, 2005; Pueyo, Bawakyillenuo, et al., 2020; Pueyo & Maestre, 2019). The

descriptive component is not elaborated further in this chapter, as its primary function was to support sampling interpretation and contextualise the subsequent analytical layers. In contrast, the MTF analysis and the semantic strand form the core diagnostic tools of the study and are each discussed in detail in the sections that follow.

6.2.2.1 Adapting the MTF

The MTF assesses energy access through a tiered system (tiers 0-5) that incorporates multiple dimensions, including capacity, availability, reliability, affordability, legality, convenience, health, safety, and quality (Bhatia & Angelou, 2015). Each tier reflects a specific threshold of service quality, enabling granular identification of where deficits persist.

In applying the MTF, this study focused on productive use attributes for both electric and non-electric energy carriers. The quality attribute was excluded due to limited data availability, but the remaining dimensions were fully assessed. In two areas, reliability and affordability, the analysis adapted the original MTF thresholds to improve sensitivity to field conditions. For reliability, tier 3 and tier 4 were expanded to reflect 2.1-10 hours and >10.1 hours of unscheduled outages per week, respectively, recognising that these outage durations significantly affect MSME operations. For affordability, a new threshold was introduced for costs exceeding twice the national grid tariff, reflecting a condition occasionally encountered by enterprises relying on expensive fuels or informal market rates.

To operationalise the framework, energy consumption values were standardised into kWh using LHV, fuel density (where needed), and appliance-specific efficiency factors sourced from the literature (Ballard-Tremeer & Jawurek, 1996; Ekouedjen et al., 2020; Garg et al., 2006; Habib et al., 2004; Islam et al., 2022; Kanase et al., 2021; Statistics Netherlands, 2025; Stiel & Skyllas-Kazacos, 2012). See Appendix B for more details on the respective conversion factors used for each fuel.

Energy prices were converted into USD using average exchange rates from national central banks. Official electricity tariffs were retrieved from national regulatory agencies, and benchmarked against reported enterprise expenditures to assess affordability (Egyptian Electric Utility and Consumer Protection Regulatory Agency (EgyptERA), 2022; Energy and Petroleum Authority (EPRA), 2023; Energy and Water Utilities Regulatory Authority (EWURA), 2021; Kenya Power

and Lighting Company (KPLC), 2023; Nigerian Electricity Regulatory Commission (NERC), 2024; Public Utilities Regulatory Commission Ghana (PURC), 2023). See Appendix C for more details on the respective electricity tariffs used for this study.

Backup energy sources were excluded in alignment with MTF guidelines, which define such measures as temporary coping strategies not to be counted toward access tiers (Bhatia & Angelou, 2015).

The tier classification process was harmonised across all assessed attributes to ensure analytical consistency, despite variations in how thresholds were defined within the original framework. In several cases, tier designations were clear and mapped directly to a specific tier, such as tier 3, tier 4, or tier 5. However, other attributes were described using broader, less precise ranges (e.g., tier 0-3 or tier 4-5), making interpretation more ambiguous. To resolve this and maintain uniformity across the dataset, the upper bound of any stated range was used as the final tier classification for that attribute. For example, a range of tier 0-3 was recorded as tier 3.

Following the methodology of the MTF, each enterprise was ultimately assigned a composite (final) energy access tier determined by the lowest value observed across the eight attributes. While this rule creates a conservative estimate of energy access, it also ensures that critical deficits are not masked by higher performance in other areas. The matrix applied is summarised in Table 10, adapted from Bhatia & Angelou (2015), and expanded to reflect the custom thresholds used in this study.

Table 10. Multi-tier matrix for measuring access to productive applications of energy

Attribute	Energy carrier	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Capacity	Electric	Not specified	Min. 3W	Min. 50W	Min. 200W	Min. 800W	Not specified
	Non-electric	Not specified			Partially meets requirements	Largely meets requirements	Fully meets requirements

Availability	Electric	Not specified	Min. 2h	Min. 4h	Min. 50%	Min. 75%	Min. 95%
	Non-electric	Not specified			Partially meets requirements	Largely meets requirements	Full meets requirements
Reliability	Electric	Not specified			Severe impact (outage above 10.1h/week)	Moderate impact (outage 2.1-10 h/week)	Little / no impact (outage up to 2h/week)
	Non-electric	Not specified			Severe impact (outage above 10.1h/week)	Moderate impact (outage 2.1-10 h/week)	Little / no impact (outage up to 2h/week)
Quality	Electric	Not specified				Quality issues with moderate impact	No quality issues or little (or no) impact
	Non-electric	Not specified				Quality issues with moderate impact	No quality issues or little (or no) impact
Affordability	Electric	Cost > 2x grid tariff				Cost ≤ 2x grid tariff	Cost ≤ grid tariff
	Non-electric	Cost > 2x grid tariff				Cost ≤ 2x grid tariff	Cost ≤ grid tariff
Legality	Electric	Energy is purchased from an informal seller				Energy bill is paid to an authorised entity	
	Non-electric	Energy is purchased from an informal seller				Energy bill is paid to an authorised entity	
Convenience	Electric	Not specified				Moderate impact on productive activity	Little / no impact on productive activity
	Non-electric	Not specified				Moderate impact on	Little / no impact on

				productive activity	productive activity
Health	Electric	Use of non-BLEENS indoors	Use of non-BLEENS outdoors or with smoke extraction	Use of BLEENS	
	Non-electric	Use of non-BLEENS indoors	Use of non-BLEENS outdoors or with smoke extraction	Use of BLEENS	
Safety	Electric	Not specified		Energy solutions caused accidents that did not require professional medical assistance	Energy solutions did not cause any accidents
	Non-electric	Not specified		Energy solutions caused accidents that did not require professional medical assistance	Energy solutions did not cause any accidents

Notes: This table presents the quality attribute from the MTF for illustrative purposes only. Due to data limitations, this attribute was not included in the formal analysis. The colour coding applied here differs from the original MTF scheme and has been adapted to align with the visual convention used throughout this study: dark red (tier 0), light red (tier 1), orange (tier 3), light green (tier 4), and dark green (tier 5), representing a gradient from poor to high energy service performance. Not specified tiers were coloured in light grey.

While the MTF itself does not contain gender-specific dimensions, it was applied here exclusively to women-owned and co-owned enterprises to assess the energy conditions under which they operate. The gender lens lies in the sampling strategy, not in the structure of the framework. Likewise, although higher MTF tiers generally indicate better energy service adequacy, they do not directly capture business performance or productivity outcomes. To address this, the framework was extended with a set of targeted analytical refinements designed to link energy access attributes with enterprise-level financial realities and behavioural indicators, namely, benchmarking reliability and availability against national grid performance, analysing affordability through energy expenditure relative to

business revenues, exploring cost-profit dynamics, and assessing willingness to invest in renewable solutions.

Third, and as a final component of the overall three-layered analytical structure, semantic content analysis was conducted on open-ended interview responses, which is presented in the next section.

6.2.2.2 Semantic analysis of open-ended responses

In parallel with the MTF-based assessment, qualitative data drawn from open-ended interview responses were subjected to semantic content analysis. Thematic categories were developed to align with the study's research aims and refined through iterative review of interview transcripts. The analysis focused on three broad domains: (1) Business challenges related to the gender of the entrepreneur, including experiences of bias, restricted mobility, work-life balance struggles, and unequal access to technical knowledge or resources; (2) Barriers to renewable energy adoption, such as limited awareness, financial inaccessibility, technology gaps, and facility constraints; and (3) Drivers of renewable energy adoption, including economic motivations, reliability concerns, environmental values, and improved safety or convenience.

Each response was coded according to these categories, allowing for the identification of recurring patterns and context-specific dynamics across the enterprise sample. A full list of the thematic variables and descriptions used in the coding process is provided in Appendix C.

6.3 Results

This chapter presents the core findings from the face-to-face interviews with 40 women entrepreneurs across the seven African focus countries, offering a detailed account of their energy access conditions and renewable energy adoption potential. Building on the sampling and methods described earlier, the results are structured to address the two guiding research questions concerning the nature of productive energy access and the barriers and drivers shaping women's uptake of renewable energy technologies.

The analysis begins with a profile of the enterprises and their sectoral, geographic, and ownership characteristics, before turning to the specific energy-intensive processes and appliances in use. It then applies the World Bank's MTF to assess energy access performance across both electric and non-electric carriers.

Finally, it explores the challenges and opportunities faced by women entrepreneurs in adopting renewable energy, drawing on both quantitative indicators and qualitative reflections from the field. Together, these insights provide a grounded and multidimensional understanding of energy use in women-owned micro- and small-sized enterprises.

6.3.1 Sample overview

The resulting dataset comprises 40 micro- and small-sized enterprises operating across Egypt, Ghana, Kenya, Malawi, Nigeria, Tanzania, and Tunisia. Although equal representation from each country was the initial aim, this proved difficult due to field-level constraints. For instance, only one enterprise from Egypt was included in the final dataset, while Nigeria alone accounts for one-third of all interviews. The remaining countries each contributed between 10% and 18% of the total sample (see Figure 14). In terms of sectoral distribution, the sample includes a slightly higher share of food enterprises (57%) compared to textile enterprises (43%), ensuring a reasonably balanced representation of both industry domains.

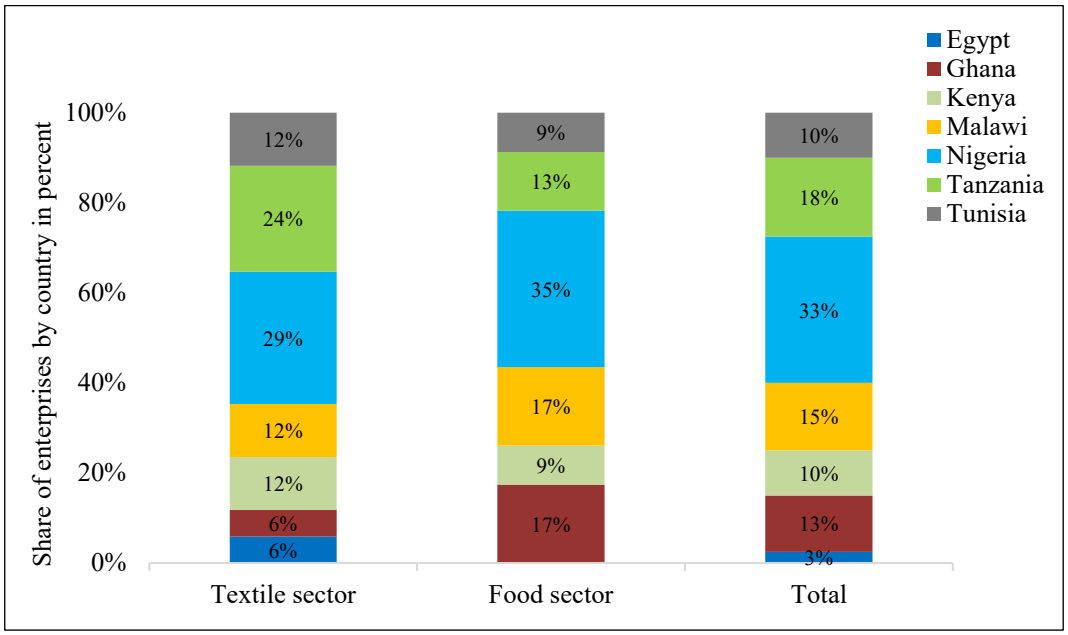

Figure 14. Sample distribution by country and industry sector

The enterprises are further categorised by their ISIC classification. Food sector enterprises are distributed across ISIC Divisions 01 (Crop and animal production), 10 (Manufacture of food products), 21 (Manufacture of beverages), and 56 (Food and beverage service activities). However, ISIC Division 10 is the dominant

category, accounting for around 78% of all food enterprises, reflecting a strong concentration in food processing and manufacturing. On the textile side, businesses fall under ISIC Divisions 13 (Textile manufacturing), 14 (Wearing apparel), and 15 (Leather and related products), with ISIC 14 (Manufacture of wearing apparel) representing 77% of textile enterprises.

The nature of goods produced varies significantly between the two sectors. Textile enterprises predominantly focus on batik and dyed fabrics (ISIC 13), garments and accessories (ISIC 14), and, to a lesser extent, leather footwear (ISIC 15). In contrast, the food sector is characterised by a broader array of outputs. These include various forms of flour (from maize, peanuts, and sweet potatoes), baked goods, porridge, dairy products, smoked and dried fish, preserved fruits and vegetables, spices, cooking oils, and beverages. Enterprises classified under ISIC Division 56 operate catering and food service businesses that prepare meals for local markets or institutions.

Ownership structures reflect the gendered focus of the study. More than half of the enterprises (55%) are owned by a sole female, while an additional 43% are gender-diverse enterprises (i.e., jointly owned by men and women). A very small fraction (2%) represents female-female co-ownership models. Sectoral breakdowns reveal some notable patterns. In the textile sector, 60% of enterprises are owned by a sole female, and around one-third are gender-diverse, with only one business under female-female ownership. In the food sector, the division is more evenly split, with sole female ownership and gender-diverse co-ownership each accounting for approximately half of the sample.

In terms of legal and operational structures, most enterprises (90%) operate as for-profit entities, a trend that is more pronounced in the food sector. While 90% of food businesses follow a for-profit model, this figure is slightly lower in the textile sector at 80%, where a small number of not-for-profit or hybrid enterprises also exist (20%), typically involved in skills training, upcycling, or community-based production.

The sample is relatively homogeneous in size, comprising exclusively micro- and small-sized enterprises. Overall, micro-enterprises dominate (63%) compared to small-sized enterprises (38%). Size distribution varies by sector: the food sector skews heavily toward micro-scale operations (around 75%), whereas the textile sector shows a more balanced division, with half of the enterprises classified as micro-sized.

Workplace location reveals distinct patterns across sectors, closely aligned with gendered occupational norms. Overall, 60% of enterprises operate from dedicated business premises, while 33% are home-based, and the remaining 7% combine both settings. In the textile sector, 71% of enterprises are based in dedicated facilities, reflecting the spatial and infrastructural demands of textile manufacturing, garment, apparel, and leather production. By contrast, food-related enterprises exhibit greater flexibility: just over half operate from external locations, while more than one-third are home-based, and 13% function from both home and external sites. This tendency for food enterprises to be situated within the home is likely shaped by sectoral characteristics that align with prevailing gendered work patterns (Asibey et al., 2021; Pueyo & Maestre, 2019). Food processing often permits the adaptation of domestic spaces for commercial use, allowing women to reconcile income generation with caregiving responsibilities and to build on existing household cooking infrastructure. As such, the concentration of home-based enterprises in the food sector may reflect both practical constraints and socio-cultural expectations that continue to shape women's entrepreneurial pathways.

A full breakdown of enterprise-level variables, including geographic spread, ISIC classification, ownership configuration, size, and location, is presented in Appendix C. Figure 15 summarises the sectoral and demographic distribution of the sample.

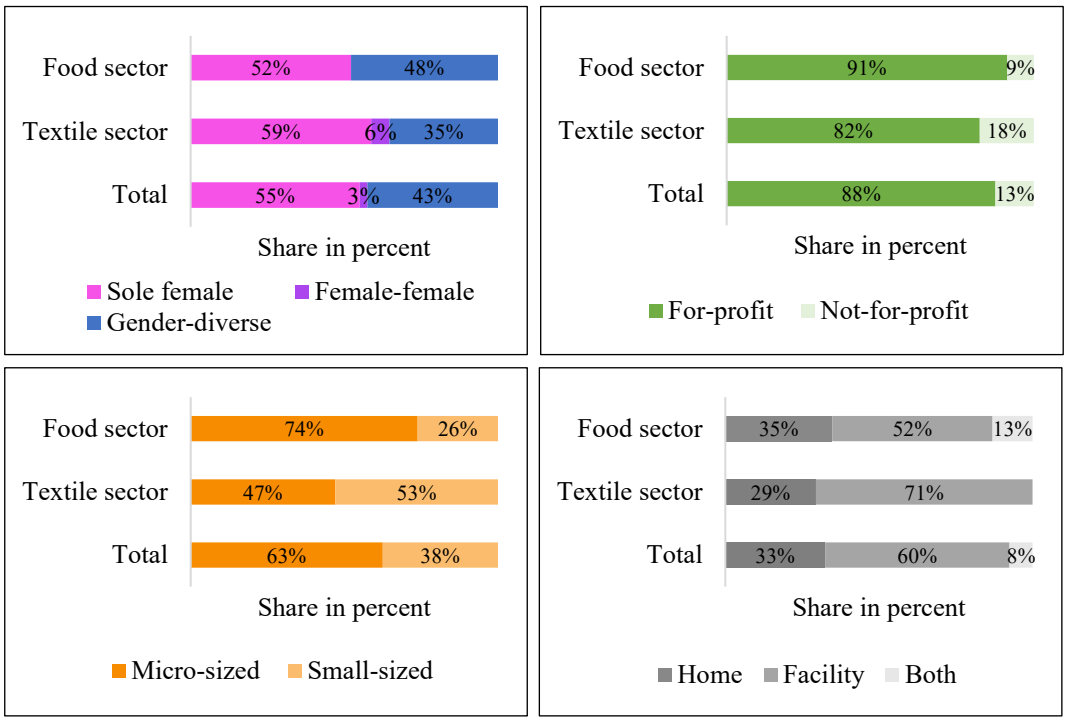

Figure 15. Sectoral and demographic characteristics of the sample

Together, these enterprise characteristics offer essential context for better understanding the variation in energy access conditions, performance tiers, and technology choices across the sample, and hence, form the basis for the subsequent sections.

Building on this enterprise-level profile, the next section delves deeper into how these women-owned businesses use energy in their day-to-day operations. Beyond understanding who the entrepreneurs are and where they operate, it is essential to explore how they utilise energy for production, what processes drive their businesses, which appliances are central to their value chains, and what energy carriers support these functions. This technical mapping of energy-intensive practices and associated equipment forms the foundation for assessing energy access performance, identifying service gaps, and designing renewable energy solutions tailored to women-owned enterprises.

6.3.2 Key energy-intensive processes and appliance specifications

This section presents a detailed inventory of energy-intensive processes and corresponding appliance specifications observed across the 40 enterprises in the study sample. These data provide critical insight into the real-world technical

configurations shaping productive energy demand among women entrepreneurs and, in doing so, create a necessary empirical baseline for subsequent tier analysis using the MTF. The full dataset is archived in the Mendeley Data repository and can be accessed at Gad & Leone (2025).

Across the sample, 95% of enterprises are grid-connected, with only two businesses, both from the food sector and located in Nigeria and Malawi, operating entirely off-grid. However, these off-grid cases illustrate different underlying dynamics. In Malawi, the enterprise is situated in a location without existing grid infrastructure, rendering connection infeasible. In contrast, the Nigerian enterprise, despite being within proximity to the grid and even previously connected, actively opted out of using the service. This decision stemmed from prohibitive connection costs and persistent service unreliability, factors that mirror broader patterns identified in Chapter 5, where enterprises nominally within grid reach remained unconnected, potentially due to cost barriers, administrative hurdles, or informal settlement status.

The overwhelming reliance on electricity, particularly grid electricity, underscores its foundational role in productive activities. Yet, electricity alone is rarely sufficient since the required energy services for productive uses are multiple. A significant share of enterprises, especially in the food sector, also depend on thermal energy, using non-electric energy carriers such as LPG, petrol, diesel, charcoal, firewood, and briquettes. As shown in Table 11, 87% of food enterprises and 100% of textile enterprises use grid electricity. Meanwhile, 78% of food and 35% of textile businesses report non-electric energy demands, and between a quarter and a third of enterprises across both sectors respectively report using fuel-powered backup solutions.

Table 11. Electric and non-electric demand, as well as fuel-powered backup solutions by industry sector

Sector	Electric demand (electric grid)		Fuel-powered backup solution (generator)		Non-electric demand (fuel)	
	number	percentage	number	percentage	number	percentage
Food	20	87%	5	22%	18	78%

Textile	17	100%	6	35%	6	35%
Total	**37**	**93%**	**11**	**28%**	**24**	**60%**

Electric and thermal loads remain modest in most cases, with only a few enterprises reporting peak appliance power ratings above 10 kW. The largest recorded power installed capacity was a 75-kW grinder in a Kenyan food enterprise. Most equipment in both sectors operates well below this threshold, suggesting that low-to-medium energy tiers are sufficient for a substantial share of processes.

In the food sector, energy-intensive processes span a wide range of activities, including cooking, baking, roasting, drying, refrigeration, freezing, milling, blending, packaging, and for dairy production, pasteurisation and homogenisation. Cooking temperatures typically range between 90-220°C, with appliance power ratings between 2.4-6 kW for ovens and stoves. Drying processes, which are common in the processing of spices, fruits, and vegetables, involve solar or electric dryers operating at 45-90°C and typically consuming 1-2 kW per unit. Milling and grinding are among the most variable sub-processes in terms of power ratings, ranging from small grinders (<1 kW) to heavy-duty equipment exceeding 40 kW. Refrigeration and freezing are widespread and performed with relatively low energy draw, usually below 0.03 kW power rate per unit, except in the case of one enterprise that operates a large cold room drawing up to 3.5 kW.

In the textile sector, the most common energy uses are associated with ironing, sewing, and fabric treatment. Irons typically draw 1-2 kW and operate at temperatures of 110-180°C. Sewing machines are present in varying numbers, from a few units in micro-enterprises to as many as 100 machines in small-scale garment workshops. While individual sewing machines have low energy demands (typically <0.4 kW nominal power, occasionally up to 1 kW), the cumulative draw in larger enterprises becomes significant. Other common practices include wax heating, water boiling, text printing, and use of glue guns and stamping machines, often powered by grid electricity, LPG, or charcoal. Textile enterprises also report heat requirements for fabric preparation and dye fixation, typically between 60-100°C.

Table 12 presents a comprehensive breakdown of these appliances by sector and ISIC Division, detailing appliance counts, energy carriers, power ratings (both measured and those inferred from MTF benchmarks), as well as temperature requirements. While the MTF provides a valuable reference for estimating energy needs (Bhatia & Angelou, 2015), its indicative power thresholds for productive

applications frequently underestimate actual equipment capacities observed in the field, especially for energy-intensive processes such as grinding and milling, water pumping, or refrigeration. Moreover, the MTF often lacks the granularity to specify equipment-level details across diverse sectors, with substantial information gaps in appliance typologies and performance benchmarks. These limitations underscore the critical importance of collecting disaggregated, sector-specific data to inform energy planning, technology sizing, and investment design.

Table 12. Major energy-intensive processes by industry sector and ISIC Division

Sector ISIC division	Appliance count	Sub-application	Appliance type	Electric power rating measured (kW)	Electric power rating as per MTF (kW)	Energy carrier	Temperature (°C)
Food							
01	1	Grinding	Oil press	30	0.15-1	GE	None
	1	Irrigation	Irrigation pump	4	Not available	GE	None
	1	Water pumping	Water pump	7.5	0.48-1.2	PV	None
	1		Water pump	7.5	0.48-1.2	D	None
10 and 56	2; 3	Air conditioning	Air conditioner	1.12	1.5	GE; D; P	+18 to +21
	1; 2; 6	Cooking, baking, and roasting	Electric oven/stove	2.4; 6	1.5	GE; D	+90 to +220
	1; 2		LPG oven/stove	Not available	Not available	LPG	+120 to +220
	1		Roaster	0.4	0.8-1.2	GE; LPG	+180
	1	Cooling	Water chiller	50	Not available	GE; PV; D	0

1	Dairy production	Pasteuriser	14.92	Not available	GE; PV; D	+4 to +90
1		Homogeniser	30	Not available	GE; PV; D	none
1		Cream separator	7.5	Not available	GE; PV; D	none
1		Butter churn	6	Not available	GE; PV; D	+4
3		Milk tank	Not available	Not available	B	+4
1		Cream heater	Not available	Not available	B	+80 to +90
1; 3	Drying	Dryer	0.89; 1; 1.13; 1.5; 1.55; 2.2; 7.4	Not available	GE; S; D; P	+45 to +90
3	Drying and smoking	Kiln	Not available	Not available	LPG, C, F	+85 to +90; +30 to +40
1; 2; 7	Freezing	Freezer	0.02; 0.27; 3.5	0.36	GE; PV; P; D	-18 to -4
1	Frying	Stove	Not available	Not available	LPG	+175 to +190
1; 3	Grinding and milling	Juicer	0.02; 0.28; 0.55; 0.9	Not available	GE; P	None
1; 2; 3; 5; 10		Blender	0.3-0.5; 0.35; 0.7; 0.74; 1.2; 1.3; 1.35; 1.5; 3; 3.7; 4	0.15-1	GE; PV; D; P	None
1; 2		Grinder	0.02; 0.3; 0.35; 0.5; 0.55; 2.2; 3; 3.7; 7.08;	0.15-1	GE; PV; D; P	None

				10.62; 40; 75			
	1		Hammer mill	22	Not available	GE; PV; D	None
	1	Heating	Stove	Not available	1.5	LPG; C	+100 to +120
	1		Kettle	1.9	1.5	GE; D; P	+100
	1		Microwave	1.5	0.5-2	GE; D	+90 to +100
	1		Food warmer	Not available	Not available	LPG	+60 to +80
	3	Packaging	Automated packaging	0.01; 0.08; 0.2; 0.44; 1.4; 3.5; 4.6; 7.5; 20	Not available	GE; PV; D; P	none
	1		Sealing	0.03; 0.42; 0.65; 1.8; 2	Not available	GE; D; P	+120 to +160
	1; 2; 5	Refrigeration	Fridge	0.03; 0.04	0.03	GE; D; P	+3 to +8
	1; 2	Sanitation	Equipment cleaner	1.5; 3; 7.5	Not available	GE; PV; D	+45 to +75
21	1	Drying	Closed room dryer	Not available	Not available	S	+60 to +80
	1	Grinding and milling	Oil press	0.4	0.15-1	GE	None
	1		Grinder	1.5	0.15-1	GE	None
Textile							
13	1; 3	Heating	Wax heater, Stove	0.75	Not available	GE; LPG	+60 to +80
	1; 2	Ironing	Iron	2; 2.2	1.1	GE	+110 to +180

	1	Rinsing	Washing machine	0.5	0.5	GE	+40
	1	Water boiling	Stove	Not available	3.5	LPG; C	+100
	1		Kettle	1.9	Not available	GE	+100
14	1; 5; 6	Air conditioning	Air conditioner	1.12; 1.5	1.5	GE; D; P	+18 to +21
	1; 2	Cutting	Cutting device	0.06; 0.1; 0.25; 1.7; 8	Not available	GE; P	None
	1	Heating	Glue gun	0.04	Not available	GE; P	+120 to +160
	1		Text printing machine	1.75	Not available	GE	+135 to +140
	1; 2; 3; 4	Ironing	Iron	0.25; 1; 1.2; 1.25; 1.6; 1.7; 2; 2.2; 2.4; 9.1	1.1	GE; D; P; C	+110 to +180
	2; 3; 4; 5; 6; 7; 10; 20; 22; 36; 62; 100	Sewing	Sewing machine, embroidery, singer, and overlock	0.14; 0.25; 0.4; 0.55; 0.6; 0.87; 1; 1.14	Not available	GE; P; D	None
15	2	Filling	Filler machine	0.55	Not available	GE; P	None
	1	Heating	Blow dryer	2	1-2.5	GE: P	+50
	1		Stamping machine	0.8	Not available	GE; P	+130 to +180
	1	Ironing	Iron	0.8	1.1	GE; P	+110 to +180
	1	Moulding	Burner	Not available	Not available	LPG	+50

3	Sewing	Sewing machine	0.25	n/a	GE; P	None

Notes: ISIC Divisions are described as follows: 01 Crop and animal production, hunting, and related service activities; 10 Manufacture of food products; 13 Manufacture of textiles; 14 Manufacture of wearing apparel; 15 Manufacture of leather and related products; 21 Manufacture of pharmaceuticals, medicinal chemical, and botanical products; 56 Food and beverage service activities.

Abbreviations: °C = degree Celsius; B = briquettes; C = charcoal; D = diesel; F = firewood; GE = grid electricity; kW = kilowatt-hour; LPG = liquified petroleum gas; P = petrol; PV = solar photovoltaic; S = direct or indirect sun irradiation

The data also show a wide variability within each ISIC category. For example, food enterprises in ISIC 10 employ grinding technologies ranging from manual blenders (<1 kW) to automated industrial grinders exceeding 70 kW. Similarly, textile enterprises under ISIC 14 may operate one or two irons for artisanal production or dozens of sewing machines in more formal workshops. This heterogeneity reinforces the need for flexible energy planning approaches that reflect enterprise diversity, rather than one-size-fits-all prescriptions based on average load profiles.

In sum, the findings from this section, although limited, reveal not only the complexity of energy needs among women-owned micro- and small-sized enterprises but also the mismatch between real-world appliance configurations and existing global metrics. These insights underscore the need for targeted, localised energy diagnostics, particularly in the context of designing renewable energy interventions for productive use.

Having established the diversity of enterprise types, sizes, and operational settings within the sample and mapped the sector-specific energy-intensive processes and appliance configurations, we now turn to a core part of the study: assessing the quality and adequacy of energy access across these women-owned businesses. The following section applies the World Bank's MTF to evaluate the level of access to both electric and non-electric energy carriers, attribute by attribute, across all enterprises in the sample.

6.3.3 Energy access performance

To assess the adequacy of energy access in the sample, the World Bank's MTF served as the analytical foundation. Each of the 40 women-owned enterprises was

evaluated against eight MTF attributes (i.e., capacity, availability, reliability, affordability, legality, convenience, health, and safety) for both electric and non-electric energy carriers. The full assessment illustrating the level of energy access by attribute across the entire sample is enclosed in Appendix C.

The overall picture that emerges from this assessment reveals substantial variation in energy access quality. None of the enterprises in the sample reach tier 5 as a final score (the highest possible score), while a majority (57%) fell between tiers 1 and 3, indicating restricted and often unreliable energy access. Only 43% of enterprises achieve tier 4, and within the lower-performing group, 20% are confined to the very bottom tiers (1 or 2). Sectoral differences are notable: 65% of textile enterprises reach tier 4, whereas 74% of food enterprises are clustered in tiers 1 to 3, underscoring a performance gap between the two sectors.

A closer look at regional patterns shows that the highest-performing enterprises are concentrated in North Africa. Four out of five enterprises from Egypt and Tunisia achieve a final score of tier 4, with one Egyptian enterprise reaching tier 5 for electric access, the highest score in the sample. These outcomes reflect the relatively advanced grid infrastructure and energy service reliability typical of North African contexts. The one exception is a Tunisian enterprise whose lower score stems from reliance on an off-site olive processing facility, which introduces additional costs and logistical inefficiencies that negatively impact its tier classification. These findings support the view that enterprises operating in more mature energy infrastructure contexts are better positioned to reach higher energy access tiers, at least from a technical standpoint.

When energy carrier types are examined separately, electric energy access outperforms non-electric energy access across the board. The single enterprise that achieves tier 5 for electric access is based in Egypt, reinforcing the influence of grid reliability on performance. Overall, 54% reach tier 4, while an additional 30% land at tier 3. For non-electric energy, performance is weaker: just one-third of enterprises reach tier 4, while 63% remain in tiers 1 to 3. This difference reflects both the reliance on and variability of energy carriers such as LPG, charcoal, and diesel in non-electric processes. Figure 16 provides more insights into the energy access performance by industry sector and type of energy carrier.

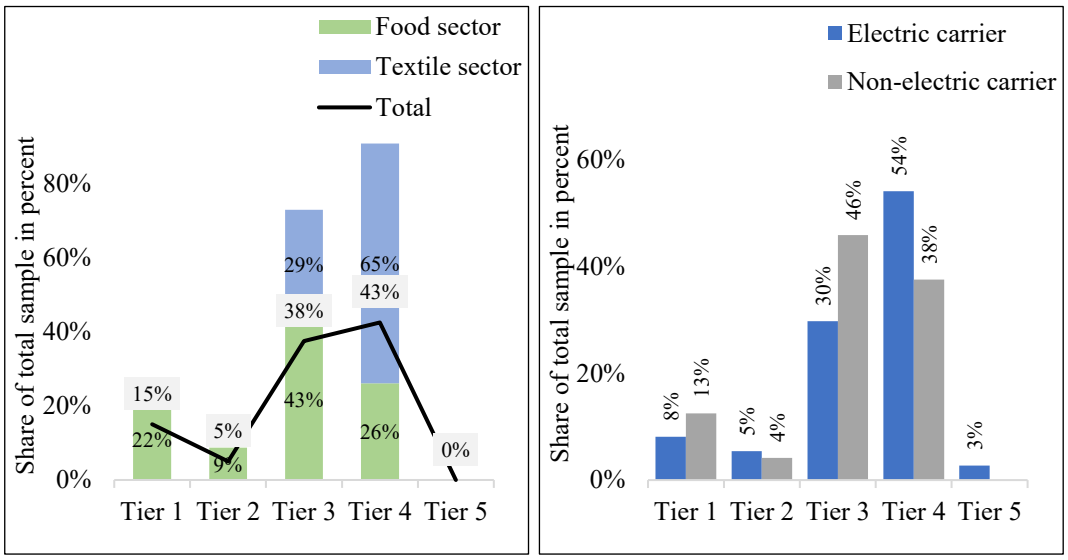

Figure 16. Total energy access tier score obtained by industry sector (left graphic) and type of energy carrier (right graphic)

A closer disaggregation of performance by sector and carrier type provides further insight. The food sector demonstrates greater vulnerability: 11% and 15% of food enterprises operate at tier 1 for non-electric and electric energy, respectively, with the majority concentrated in tiers 2 and 3. No food enterprise in the sample reaches tier 5. In contrast, the textile sector shows more promising outcomes for electric energy, with 82% of enterprises achieving tiers 4 or above. However, the picture changes for non-electric energy, where performance drops markedly: only half of textile enterprises surpass tier 3. These disparities highlight critical gaps in energy access for productive use, particularly in the food sector and for non-electric energy services more broadly (see Figure 17).

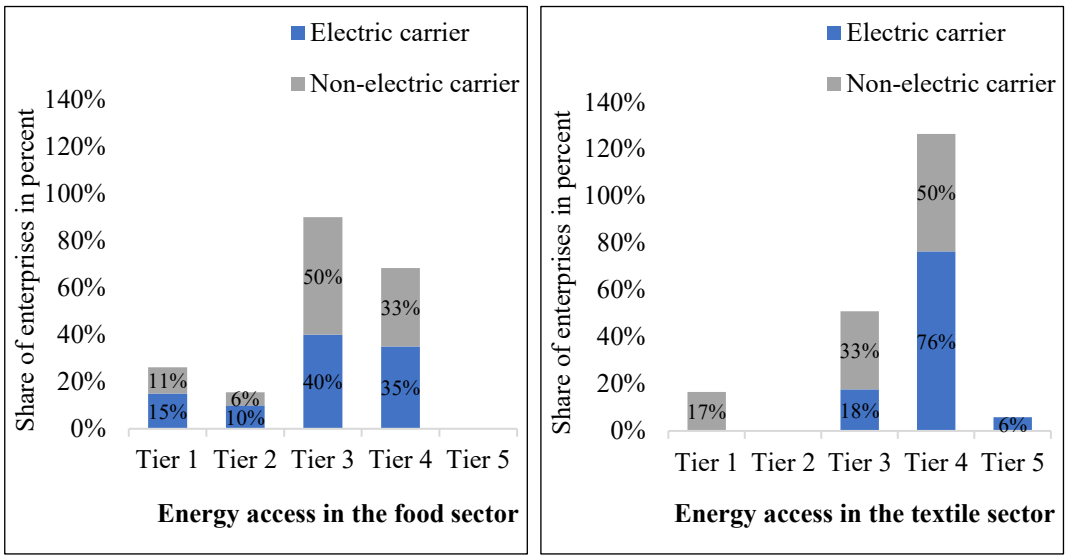

Figure 17. Distribution of enterprises across tiers in the food sector (left graphic) and textile sector (right graphic) by type of energy carrier

Evaluating the final tier scores, which integrate both electric and non-electric carrier performance (based on the lowest-scoring attribute per enterprise), 58% of the sample exhibits inadequate access (tiers 1 to 3). These enterprises are unevenly distributed across sectors: 74% of the underperformers are in the food sector, and only 26% are in the textile sector. The nature of the energy access challenges is split: 35% of these enterprises experience deficits in both electric and non-electric energy, another 35% face problems specifically with electricity, while the remaining 30% struggle primarily with non-electric carriers.

Drilling down into MTF attribute-specific performance reveals why these enterprises fell into the lower tiers. Reliability emerges as the most frequent constraint: 57% of the underperforming enterprises score only tier 3 for this attribute, indicating that unscheduled outages, often exceeding 2.1 hours per week, severely disrupt operations. Affordability is the second most common challenge, affecting 44% of the low-tier enterprises. A small but notable subset (13%) performs poorly in critical areas such as availability and health, suggesting limited hours of energy service and heightened exposure to unsafe conditions, largely due to the use of non-BLEENS energy carriers, as defined by the World Bank's MTF. Interestingly, legality does not emerge as a significant barrier; 87% of enterprises score at tier 5, as they rely on officially authorised providers.

In the food sector, poor electricity access is primarily driven by frequent outages and limited daily availability, undermining production reliability and

output consistency. In many cases, enterprises depend on shared or external facilities for electricity-intensive tasks, adding transport and coordination burdens that decrease operational efficiency. Backup systems, when present, often require manual activation and fuel procurement, further lowering convenience. For non-electric carriers, reliance on biomass, charcoal, and petrol introduces health and safety risks, particularly when burned indoors or handled without proper protective measures. These fuels also impose heavy cost burdens, reducing overall affordability.

In the textile sector, electric energy access is comparatively stronger but still hampered by grid interruptions and limited availability during peak working hours. Non-electric energy constraints arise from both health risks and cost burdens associated with traditional fuels or informal supply chains. These factors explain why a significant portion of textile enterprises still perform poorly on the non-electric dimension. Table 13 summarises the MTF attributes most responsible for limiting energy access across sectors and types of energy carrier.

Table 13. MTF attributes contributing to poor energy access (tiers 1-3) by industry sector and type of energy carrier

Energy carrier	Enterprises at tiers 1-3	Availability	Reliability	Affordability	Legality	Convenience	Health
	number	percentage	percentage	percentage	percentage	percentage	percentage
Food (total: 17 enterprises)							
electric	14	57%	79%	14%	0%	14%	0%
non-electric	14	14%	0%	50%	14%	7%	64%
Textile (total: 6 enterprises)							
electric	6	50%	33%	0%	0%	17%	0%
non-electric	4	0%	0%	25%	25%	0%	50%

Availability and reliability are key contributors to poor energy access in both sectors, but especially in the food sector, where outages regularly disrupt

temperature-sensitive or time-critical processes like baking, drying, and refrigeration. To contextualise enterprise-level data, the study findings were compared to country-level indicators from the World Bank, such as average weekly outage duration, blackout frequency, and the percentage of firms rating electricity as a severe constraint (The World Bank Group, 2024b).

Figure 18 illustrates significant disparities in outage experiences both within countries and between regional contexts, drawing on enterprise-level data (upper panel) and national-level perceptions (lower panel). In the study sample, outage severity often exceeds national averages reported by the World Bank, particularly in Ghana, Kenya, and Malawi (The World Bank Group, 2024b). Nigeria is a notable exception, where the sample data align closely with national benchmarks. In contrast, North African enterprises report minimal or no outages, with two Tunisian textile firms experiencing uninterrupted service. This aligns with national statistics, which show that both Tunisia and Egypt have comparatively low average outage durations. However, a more complex picture emerges when considering firm perceptions: despite relatively stable supply, 38% of Egyptian firms and 34% of Tunisian firms still identify electricity as a major or very severe constraint, figures that are comparable to or even higher than some sub-Saharan countries. This suggests that reliability alone does not determine perceived energy adequacy. Overall, the lower panel of Figure 13 underscores the systemic nature of grid unreliability: up to 85% of firms in countries such as Ghana and Malawi report outages, and 32-48% of firms across the dataset identify electricity as a severe constraint on productivity. These trends also echo the study's primary data: 57% of food enterprises report that limited availability negatively affects their operations, and 79% experience reliability-related disruptions. In comparison, 50% of textile enterprises cite availability challenges, and 33% report reliability issues. Taken together, these findings reaffirm that grid unreliability is a widespread barrier, though its manifestations and perceived severity vary across regions and enterprise types.

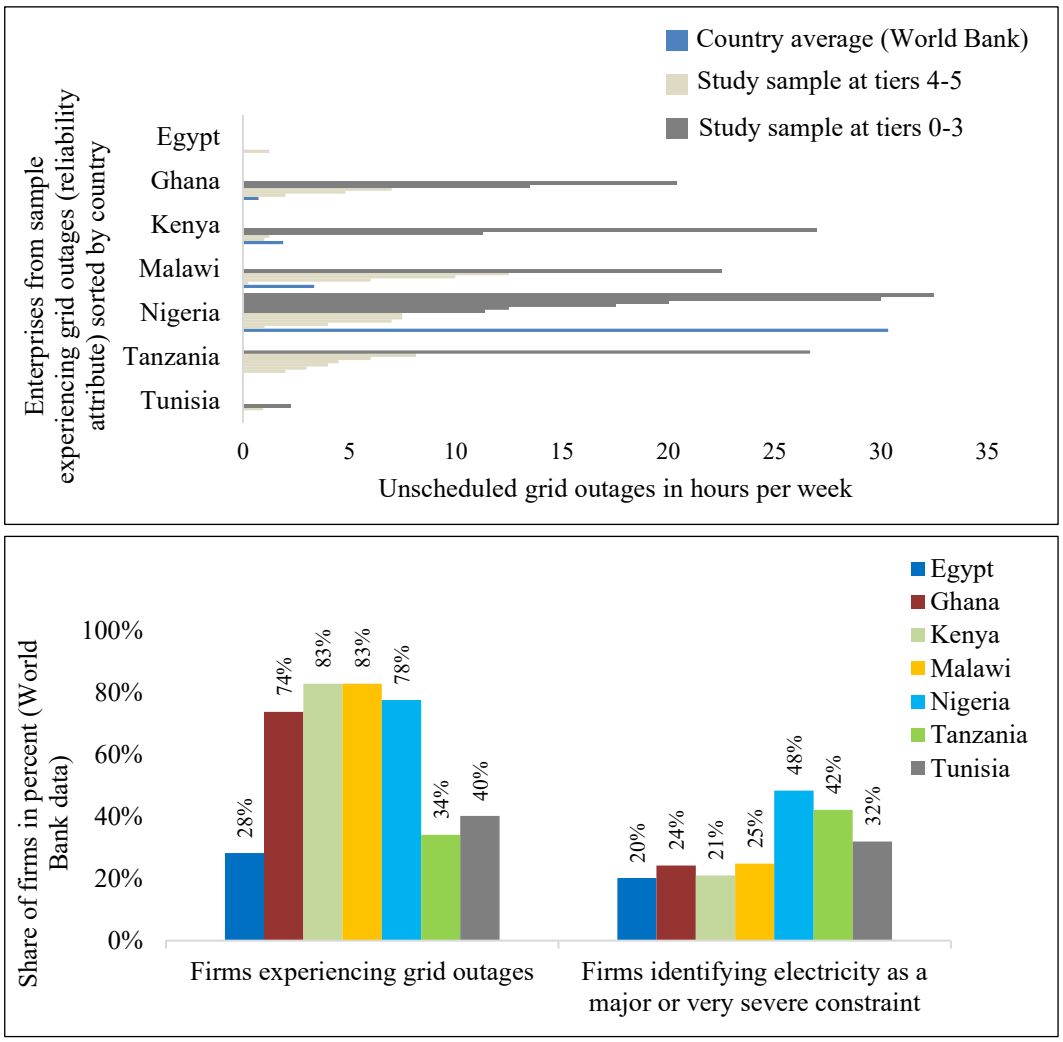

Figure 18. Grid outages across the sample in hours per week compared to national averages (upper panel) and national perceptions on grid outages and their impact on productive use (lower panel)

Notes: In the upper panel, certain enterprises are not included since they experience 0 hours of grid outages per week (2 textile enterprises in Tunisia) or do not rely on grid electricity at all (3 food enterprises, including 1 from Malawi and 2 from Nigeria). The lower panel is adapted from the World Bank Group (2024).

Beyond issues of reliability and availability, affordability emerges as another core barrier to meaningful energy access. Drawing on detailed insights from the face-to-face interviews, the study expands the analysis of affordability beyond the parameters captured in the MTF, enabling a more nuanced understanding of how cost considerations constrain energy use among women-owned enterprises. More

specifically, the interviews provided deeper insight by examining energy expenditures relative to total operating costs and revenues.

Despite challenges in data accuracy, largely due to limited bookkeeping practices among the assessed enterprises, approximately 60% of respondents were able to provide revenue data, while 65% reported expenditure figures. While these limitations warrant caution, the available data nonetheless reveal important patterns: Even enterprises classified at higher affordability tiers by MTF standards may still allocate significant shares of their budget to energy. For example, as shown in Figure 19, among tier 5 enterprises, 70% still spend 10-50% of their total expenditure on energy. Interestingly, some enterprises, particularly those classified within lower energy access tiers, reported energy expenditures that exceed their stated revenues. While this may reflect genuine financial strain or operational inefficiencies, it also raises important questions regarding data accuracy, respondent understanding of business finances, and the underlying viability of certain enterprise models. Notably, this pattern applies to two specific cases in the sample: one NGO-hybrid enterprise reporting marginal profits, and one off-grid enterprise led by owners with limited formal education. These examples underscore both the structural difficulties faced by under-resourced businesses and the interpretive challenges when assessing financial data in informal or resource-constrained contexts.

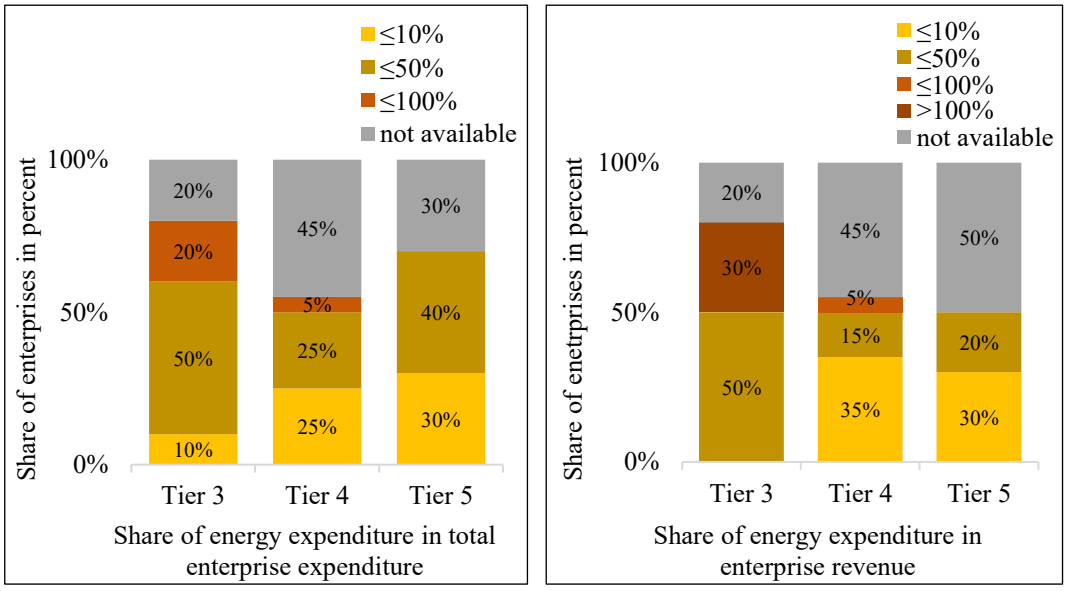

Figure 19. Comparison between affordability tiers from the MTF and the share of energy expenditure in total enterprise expenditure (left panel) and enterprise revenue (right panel)

A more granular analysis of profit margins relative to energy expenditure reveals both expected and unexpected dynamics. Enterprises with the highest profit margins, exceeding 60%, typically report that energy costs account for less than 15% of their total expenditure or revenue. These cases, primarily located in Nigeria, Tunisia, and Malawi, suggest that keeping energy costs proportionally low can support strong profitability, especially when coupled with efficient operations and robust revenue streams.

However, lower energy expenditure does not automatically translate into higher profits. Among enterprises with energy costs below 10%, many exhibit only moderate profit margins (10-33%), underscoring the influence of additional factors such as input prices, market conditions, and business scale. A mid-range group, where energy costs account for 12-30% of expenditure and 20-45% of revenue, generally report modest profitability (1-24%), suggesting that moderate energy burdens may constrain but not preclude financial viability.

More unexpectedly, a subset of enterprises with exceptionally high energy costs, 30-60% or even approaching 100% of total expenditure, nonetheless report robust profit margins between 20% and 55%. This counterintuitive outcome is often tied to lean business models where energy is the principal cost driver, and other expenditures, such as raw materials, labour, or distribution, are minimal. Notably, these enterprises are predominantly engaged in food processing, with one operating in the restaurant sector, and they tend to be micro-sized businesses run from home-based premises. In such contexts, energy-intensive operations can remain viable and even highly profitable when value generation outweighs the limited complexity of their input structures.

As Figure 20 illustrates, the relationship between energy costs and profitability is far from linear. Rather than serving as a direct constraint, energy expenditure interacts with broader enterprise structures, including sectoral characteristics, value-added potential, and cost composition, to shape overall financial performance.

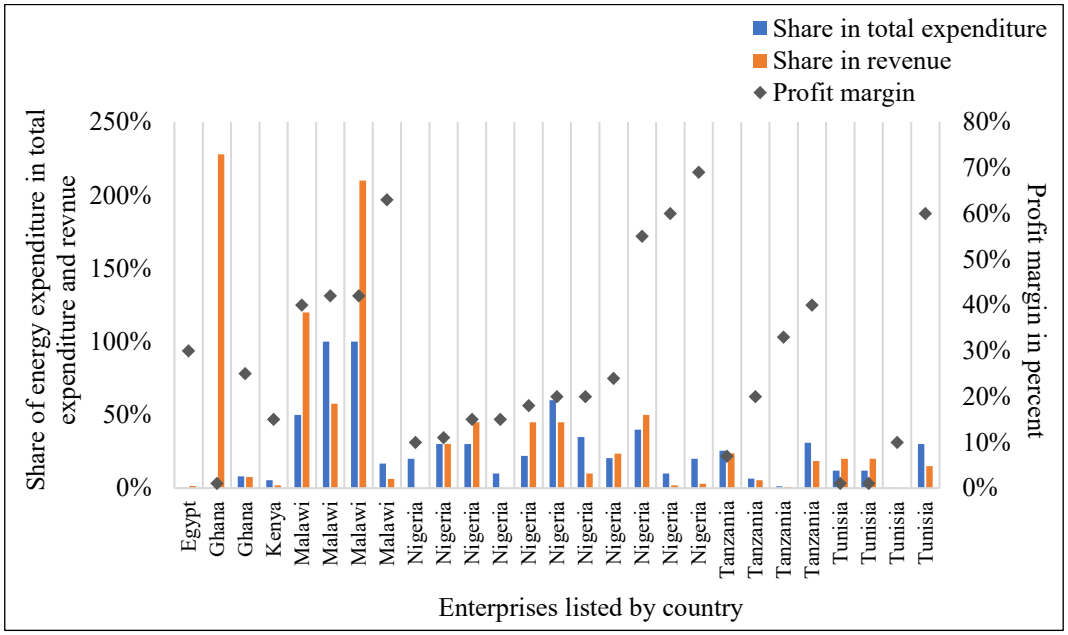

Figure 20. Comparison of the share of energy expenditure in total enterprise expenditure and enterprise revenue with enterprise profit margin by country

Notes: Only enterprises with available data on the share of energy expenditure in total expenditure and/or revenue are listed, making up 67.5% of the total sample.

Finally, the willingness to invest in renewable energy solutions or pay for enhanced energy services was assessed as a proxy for both perceived need and readiness to transition. Most entrepreneurs had not considered specific investments before the interview, but expressed openness if the technology would enhance their energy supply or business operations.

The findings show that over half (58%) prefer monthly payment schemes, while 31% are willing to make investments in new technologies, either through a loan (18%) or a one-time payment from savings (13%). Another 8% are expressing a rather open willingness to invest in renewables or pay for enhanced services. Figure 21 visualises the distribution of financing preferences across industry sectors.

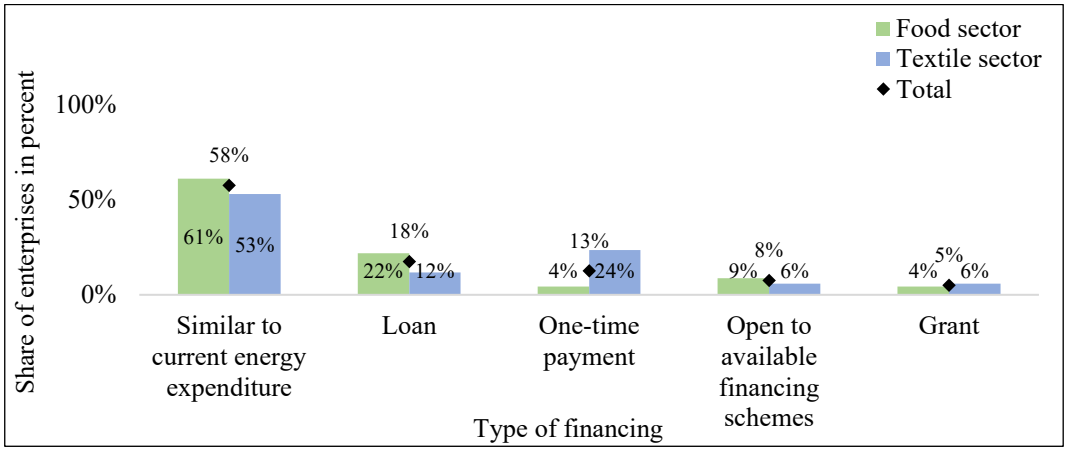

Figure 21. Willingness to invest in or pay for renewable energy technologies by financing type and industry sector

When asked about their willingness to pay for improved energy services relative to current energy expenditure, enterprises revealed diverse investment preferences: A plurality (44%) indicated they would be comfortable paying an amount equivalent to their existing monthly energy costs. Another 26% were willing to pay between 50% and 75% of their current expenditure, while 13% expressed a preference to pay less than half. Notably, 17% of respondents are open to exceeding their current energy spending, drawing on profits or savings, suggesting a readiness among some enterprises to prioritise long-term energy upgrades despite short-term financial constraints.

These findings highlight a strong latent demand for clean energy solutions, particularly if accompanied by flexible payment mechanisms. They also point to the need for tailored financial products that accommodate the diversity of enterprise capacities and ownership structures across sectors.

6.3.4 Challenges and opportunities

Building on the quantitative analysis of energy access performance in the previous sections, this part of the chapter turns to a qualitative investigation of the structural, behavioural, and perceptual factors that shape how women entrepreneurs engage with energy systems. It offers interpretive depth that complements the technical metrics explored earlier, providing insights into how women entrepreneurs experience and navigate constraints that are often invisible in energy performance data. It brings into view not only the practical hurdles to adopting cleaner energy systems, but also the broader entrepreneurial environment in which such decisions unfold.

While some gender-specific challenges, such as restricted mobility, were mentioned more frequently in North African contexts (e.g., Egypt and Tunisia), the overall pattern of reported constraints and opportunities does not support a meaningful regional distinction. Gender-biased attitudes, limited access to finance, and competing domestic responsibilities were raised across all countries in the sample. Given the qualitative nature of the data, the modest sample size, and the cross-country diversity of business contexts, this section refrains from drawing regional comparisons that could overstate what are ultimately globally entrenched gendered norms. Instead, the analysis focuses on identifying common themes that cut across geographies, sectors, and enterprise types, highlighting the systemic nature of the barriers that women entrepreneurs face.

6.3.4.1 Gender-related business challenges

Interestingly, access to energy itself is rarely cited as a gender-specific constraint. Instead, the most commonly reported gender-related challenge, mentioned by half of all respondents, is the persistence of gender-biased attitudes. These include societal perceptions that question the legitimacy, competence, or authority of women business owners. Other frequently cited constraints include restrictive gender roles, sexual harassment, difficulty maintaining work-life balance, and limitations on physical mobility. These barriers are not equally distributed across sectors. For instance, 20% of respondents, mostly in the textile sector, note that they do not experience gender-specific challenges, citing the sector's broader cultural acceptance of female participation. Yet even within this relatively inclusive environment, biases persist.

One textile entrepreneur from Dar es Salaam, involved in the manufacture of traditional fabrics, reflects on the tension between visibility and legitimacy:

> ***"Although women are mostly accepted in the fashion industry, it is still often difficult for me in the manufacturing industry to be fully accepted and seen as competent in my field. This is especially the case when I speak with government officials, presenting my ideas on promoting clean energy use for Tanzania's traditional fabric production."***

This underscores the layered nature of gender norms: while sectoral acceptance may open doors, institutional recognition and influence often remain gendered.

In the food sector, similar sentiments are expressed. A Ghanaian entrepreneur producing coconut-based products describes the subtle but persistent questioning of her qualifications:

"A lot has changed in Ghana for women and their rights. Still, I am not fully accepted as an entrepreneur; my qualifications are constantly questioned, and I feel the need to prove myself in front of the men I work with."

Restricted mobility is another recurring theme, often shaped by age, geography, or gendered expectations. One textile entrepreneur, engaged in uniform production in Kenya, explains:

"At my age, and living far away from the city, it is difficult to take the bus to Nairobi to get fabrics for sewing."

Mobility constraints are also observed in the food sector, where access to raw materials requires long-distance travel, often involving overnight stays. A Nigerian entrepreneur describes the tension between business necessity and societal limitations:

"To get high-quality red palm oil, I need to travel long distances to another state, with overnight stays. As a woman, this is very challenging in Nigeria."

Time burdens related to unpaid care work further limit entrepreneurial agency. In Malawi, a porridge flour and herbal drink producer reflects on the challenges of solo caregiving:

"As a single mother, it is very challenging to get my three children to school, feed them, and run my business."

Similarly, a rural maize mill operator explains how mechanical breakdowns intersect with caregiving duties:

"When our diesel mill breaks down or certain parts need to be repaired, which happens regularly, my husband and I rent a pickup truck and we drive to the next town for repairs, sometimes taking a couple of days. This also means that I have to leave my children and household chores behind."

Gender roles and expectations around domestic responsibilities are also noted as limitations to business operations. One Tanzanian entrepreneur involved in oil processing, who also works across the Kenyan border, explains:

"For men, it is often easier to handle certain business operations and deal with customers and government officials."

Sexual harassment presents an additional, often underreported, barrier. One Tanzanian woman running a restaurant recounts:

"As a woman, it is difficult to run a restaurant. Customers flirt and sometimes expect sexual favours."

In Malawi, a textile entrepreneur voices a similar concern:

"To get orders and sell our uniforms, potential customers expect sexual favours."

While less frequently mentioned, lack of access to resources, whether technical, financial, or land-based, is raised as a gendered challenge. One Kenyan food entrepreneur cites difficulty in acquiring the technical knowledge needed for business improvement. A Nigerian textile entrepreneur expresses how institutional exclusions shape growth limitations:

"The banks denied me several loans in the past because I am a woman. Additionally, I am not allowed to own land which further limits my plans to expand my business."

Figure 22 summarises the main self-reported business-related challenges of the women entrepreneurs from the sample.

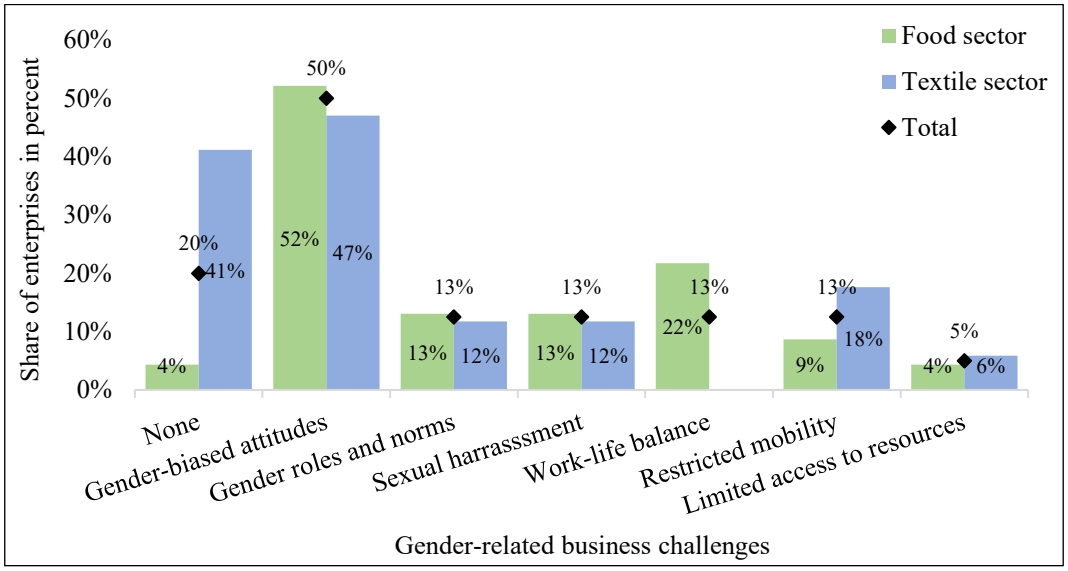

Figure 22. Self-reported business challenges reported by women entrepreneurs related to their gender by industry sector

These narratives reveal how structural inequalities intersect with the everyday decisions women entrepreneurs must make. Although gender-based constraints are not always directly related to energy, they often shape the practical feasibility of adopting new technologies. Understanding these barriers is essential for developing inclusive energy policies and business support mechanisms.

6.3.4.2 Barriers to and drivers for renewable energy adoption

Turning specifically to renewable energy adoption, the dominant constraint cited by nearly two-thirds of entrepreneurs is limited access to finance. This reflects the broader literature on gender and energy, which consistently identifies financial exclusion as a major barrier to women's participation in clean energy markets (ENERGIA et al., 2022; Pueyo & Maestre, 2019). A second key barrier, mentioned by 40% of respondents, is limited knowledge about renewable energy technologies. Many entrepreneurs had never heard of such options or lacked information about how these technologies could be integrated into their business models. A quarter of the sample expresses concerns about the availability or technical adequacy of renewable energy solutions. This group is sceptical about whether such systems could fully meet their operational needs, especially for power-intensive equipment. Only 10% of the sample identify regulatory or policy-related issues as barriers, suggesting that while governance can shape broader enabling conditions, more immediate obstacles lie in access, awareness, and system compatibility.

Despite these challenges, a strong underlying demand for renewable energy emerges. While 13% of respondents could not identify any drivers, primarily due to limited awareness, the remainder articulates clear motivations. Economic savings are the most frequently cited benefit, mentioned by 63% of all entrepreneurs. This finding is particularly important in light of the energy expenditure data presented earlier, where many enterprises spend substantial portions of their income on fuel and electricity. Environmental considerations follow closely, mentioned by half of the respondents overall. These motivations vary somewhat by sector: 65% of food sector entrepreneurs highlight environmental sustainability, compared to only 29% in the textile sector.

Grid unreliability and fuel insecurity are also key motivators. 35% of entrepreneurs are frustrated with inconsistent supply, particularly frequent blackouts and rising fuel prices, as reasons to consider renewable alternatives. A further 18% of respondents note that renewables could reduce operational disturbances such as noise, smell, or pollution caused by diesel or petrol generators. Improved safety is another benefit, cited by 8% of the sample, particularly in relation to fire risks and indoor air pollution. These insights align with existing studies that emphasise the co-benefits of decentralised clean energy for MSMEs, particularly when designed with women's health and time burdens in mind (Asibey et al., 2021; Patnaik et al., 2021).

Figure 23 presents the main barriers to and drivers for renewable energy adoption.

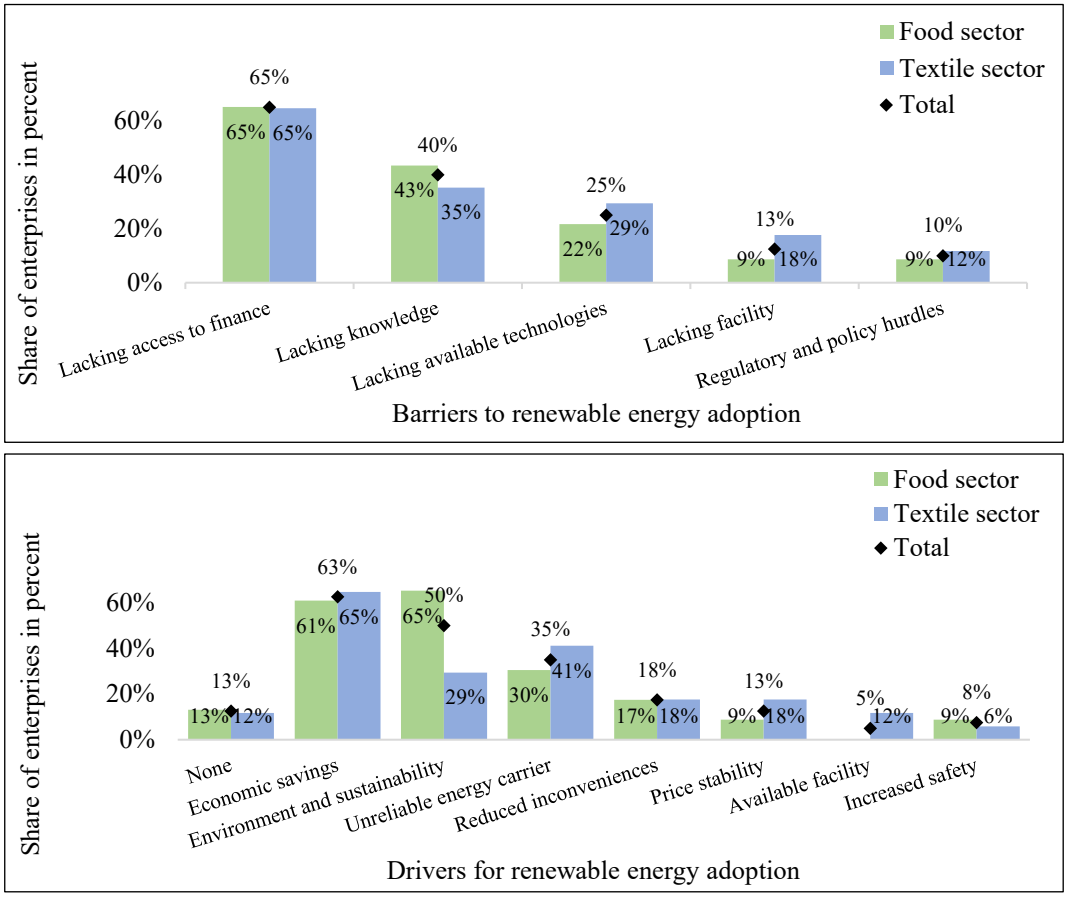

Figure 23. Self-reported barriers to (upper panel) and drivers for (lower panel) renewable energy adoption

Altogether, these findings reflect a readiness to adopt renewable energy, provided that the right financial, informational, and technical conditions are in place. Women entrepreneurs across sectors see renewable energy not only as a cleaner option but also as a tool to reduce costs, improve safety, and increase operational control. Importantly, many of these motivations stem from negative experiences with current energy systems, experiences that are further shaped by gender roles, mobility constraints, and financial exclusion. In the following discussion, these interlinked dynamics are further examined to offer a critical reflection on the findings presented so far.

6.4 Discussion

This chapter addressed the second phase of the research, focusing on face-to-face interviews and energy audits with women entrepreneurs in seven African countries. Drawing on the World Bank's MTF and guided by a mixed-methods

design, the chapter sought to answer two central research questions: (1) ***what are the key characteristics of energy access for productive use among women entrepreneurs?*** And (2) ***what barriers and drivers influence women entrepreneurs' adoption of renewable energy technologies?***

The findings offer a rich, empirical characterisation of productive energy use in women-owned micro- and small-sized enterprises, providing insight into how energy needs, access constraints, and renewable energy potential unfold across diverse sectors and national contexts. While the sample was not intended to be nationally representative, it is among the very few studies to systematically apply the MTF to the productive use context in women-owned enterprises across multiple African countries, offering a rare depth of appliance-specific, cost, and access-level data.

A first key insight relates to the multi-dimensional nature of energy access. Using the MTF allowed the study to move beyond simple binary metrics of electricity connection and instead assess energy access through a composite of eight attributes, many of which directly impact women's day-to-day operations. In doing so, the study reveals an uneven landscape. Over half of the enterprises in the sample fall within tiers 1-3, indicating inadequate energy access. This pattern is especially pronounced in the food sector, where reliance on both unreliable grid electricity and polluting fuels such as diesel, petrol or traditional biomass leads to lower performance scores for both electric and non-electric energy carriers. Even among textile enterprises, where electric access is generally more reliable, challenges remain around non-electric carriers and affordability.

A regional perspective adds further nuance. Enterprises located in North Africa consistently recorded higher final MTF scores, with one Egyptian firm reaching tier 5 for electric energy access, the highest observed in the study. This aligns with national-level data indicating stronger infrastructure and fewer reported grid outages. However, even in countries, structural constraints persist: Tunisia still reports electricity as a major constraint on productivity according to World Bank enterprise data, and Egypt performs comparably to several sub-Saharan countries on this measure. This suggests that while infrastructure maturity supports better technical access outcomes, it does not automatically translate into reduced operational or gender-related barriers. Importantly, renewable energy adoption remains both viable and urgent across regions. In sub-Saharan Africa, it offers a pathway to close persistent access gaps and transition enterprises from traditional, often polluting, fuels to more reliable and sustainable energy sources. In contrast,

in North African contexts where basic access is more established, renewables present an opportunity to enhance cost-efficiency, improve service reliability, and reduce dependence on grid-based electricity, particularly relevant for enterprises seeking greater operational resilience. Thus, tailored support measures are needed on both fronts, addressing infrastructure and service gaps where they exist, and promoting clean energy transitions even where basic access is relatively stable.

These findings confirm and expand existing research on gendered energy access. Prior studies have documented that women often face greater structural barriers in accessing modern energy for productive use, particularly in rural or informal enterprise settings (Asibey et al., 2021; ENERGIA et al., 2022; Pueyo, Bawakyillenuo, et al., 2020; Pueyo & Maestre, 2019). This study adds granularity to that body of work by highlighting how these barriers manifest in specific enterprise attributes: for example, the prevalence of outdated or inefficient appliances, poor reliability of grid electricity, and reliance on harmful or expensive fuels. Importantly, these constraints are not merely technical, they intersect with gender norms, mobility limitations, and safety concerns that shape how women engage with energy systems.

The second key insight relates to the financial dimension of energy access. Even among enterprises that score relatively well in the MTF's affordability category (which compares energy costs to national grid tariffs), the actual share of energy expenditure relative to total costs or revenue remains high. For some enterprises, energy accounted for up to 50% of operating expenditure or income, a burden that directly constrains investment capacity and business growth. These findings echo the broader literature on affordability gaps in energy transitions (Duppati et al., 2025; Ferreri et al., 2022; Kouassi & Pineau, 2011; Ogunjuyigbe et al., 2024) and suggest that affordability, as measured through grid tariffs, does not fully capture the financial pressures faced by small enterprises, especially those run by women.

At the same time, the study uncovered a notable openness among women entrepreneurs to invest in renewable energy technologies. Despite limited prior exposure or knowledge, most respondents expressed willingness to adopt cleaner and more sustainable energy systems, provided they were affordable, compatible with operational needs, and supported by accessible financing mechanisms. Preferences varied by sector and financial capacity, but the majority favoured monthly instalment schemes aligned with existing energy spending, suggesting that well-designed pay-as-you-go (PAYGo) or lease-to-own models could hold strong

appeal. These findings align with prior research on willingness to pay in productive contexts (Cerdá et al., 2024; Sundt & Rehdanz, 2015) and reinforce arguments for context-sensitive business models tailored to the productive use needs of women entrepreneurs.

Barriers to adoption, however, remain significant. The study found that the most frequently cited obstacle was a lack of access to finance, followed by limited knowledge of renewable energy technologies and uncertainty around technology suitability. These findings align closely with the broader body of gender-energy scholarship, which has consistently pointed to financial exclusion and information asymmetries as major impediments to women's participation in energy transitions (De Groot et al., 2017; Ferroukhi, Renner, et al., 2019; Pollitzer & Lee, 2020). In the present study, even when entrepreneurs expressed interest in renewables, scepticism persisted about whether such systems could deliver sufficient power or thermal energy for productive use processes.

Figure 24 synthesises the key empirical insights from this chapter, highlighting how multi-dimensional energy access, financial strain, regional contexts, and gendered constraints shape the productive use of energy in women-owned enterprises. It also distils the major barriers and enabling factors that influence renewable energy adoption across varied African contexts.

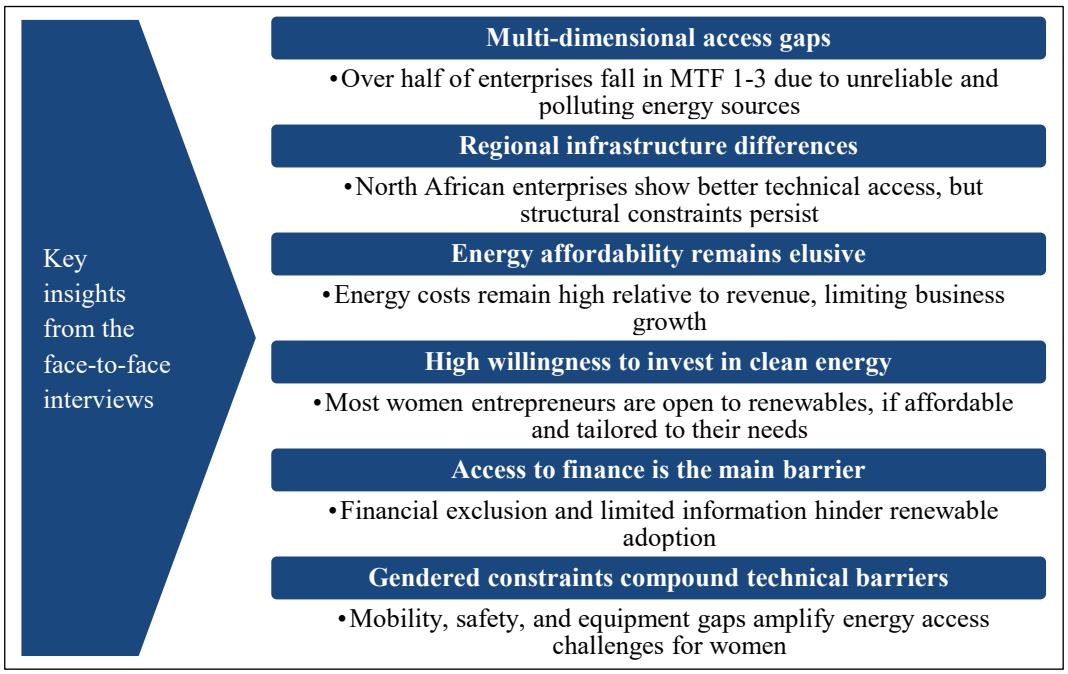

Figure 24. Key insights on productive use of energy, including barriers and enabling factors that influence renewable energy adoption among women entrepreneurs

Several methodological strengths and limitations should be acknowledged. The application of the MTF in this study provides a robust, multi-attribute framework for assessing productive energy use, adapted here to include enterprise-specific indicators such as energy costs and equipment capacity and use. This approach allowed for a more nuanced and context-sensitive analysis than is often seen in household-focused MTF applications. However, limitations persist. The small sample size, although comparable to similar studies in the field (Ceschin et al., 2023; Majumdar, 2020; Wiese, 2020), constrains the generalisability of findings. Data availability varied across enterprises, particularly for expenditure and revenue figures, which limited the ability to perform statistical tests or explore causal linkages between energy access and business performance. Future research could consider integrating this methodology into larger-scale surveys and incorporating a longitudinal dimension to better capture temporal dynamics and energy transition pathways.

Despite these constraints, the study's contributions are threefold. Empirically, it offers a detailed cross-country assessment of energy access in women-owned micro- and small-sized enterprises, using both electric and non-electric energy

carriers. Methodologically, it demonstrates how the MTF can be adapted and operationalised for productive use contexts, including affordability thresholds and equipment-level specifications. And substantively, it highlights the intersectional challenges faced by women entrepreneurs, from financial exclusion, technology and knowledge gaps to gender-based discrimination and mobility constraints. These findings offer valuable inputs for policymakers, energy providers, and financial institutions seeking to design inclusive energy access programmes.

6.5 Conclusions

This chapter has presented a detailed empirical account of productive energy access among women-owned micro- and small-sized enterprises across seven African countries. Through a structured application of the World Bank's MTF and insights drawn from face-to-face interviews, the findings reveal how energy access, energy demand, and renewable energy adoption potential intersect with gendered entrepreneurial realities. Rather than generalising, the chapter has sought to capture the complexity of women's productive energy experiences, highlighting both the structural constraints they face and their agency in navigating energy access challenges.

The analysis has also demonstrated that women entrepreneurs are not passive recipients of energy access interventions. They actively evaluate trade-offs, identify inefficiencies, and articulate clear investment preferences, especially when given the space to voice their needs in their own terms. Their decisions are shaped by sectoral requirements, domestic responsibilities, and gendered market dynamics, factors often missed in conventional energy planning.

Rather than offering simple answers, this chapter underscores the need for tailored, context-aware approaches that move beyond binary metrics and uniform solutions. It provides an essential bridge between macro-level energy access indicators and the lived realities of enterprise-level energy use.

The next chapter builds directly on this foundation. While Chapter 6 mapped patterns in access levels and adoption potential, Chapter 7 zooms in on selected enterprise case studies to examine how energy transitions are unfolding in practice. These cases draw from the same empirical dataset but zoom in on specific enterprises to examine potential energy access enhancement strategies, financing models, and operational adaptations. Through these case study analyses, the thesis moves from diagnosing constraints to exploring transition pathways.

Chapter 7

7. Sustainable energy solutions – Which techno-economic pathways can enhance energy access for women entrepreneurs?

7.1 Introduction

This chapter transitions the analysis from diagnostic assessments to the exploration of concrete technological implementation strategies. While the preceding chapters examined patterns of productive energy use (Chapter 5) and assessed enterprise-level energy access performance and the potential for renewable energy adoption (Chapter 6), this chapter moves from what is to what could be. It explores concrete pathways for clean energy adoption among women-owned micro- and small-sized enterprises in Africa, focusing on the technical viability, environmental benefits, and financing requirements of grid-connected and decentralised energy interventions across diverse contexts.

This phase of the research is guided by two interlinked questions: (1) ***how can clean energy technologies be configured to meet the productive energy needs of women-owned enterprises?*** And (2) ***what techno-economic and environmental trade-offs arise when evaluating energy transition scenarios at the enterprise level?*** These questions respond directly to the broader goal of identifying gender-responsive and environmentally sustainable energy solutions for MSMEs, while acknowledging that technology adoption is deeply shaped by both physical infrastructure and socio-economic conditions.

To that end, this chapter presents six detailed case studies from Ghana, Tunisia, Kenya, Malawi, Nigeria, and Tanzania, as presented in Figure 25.

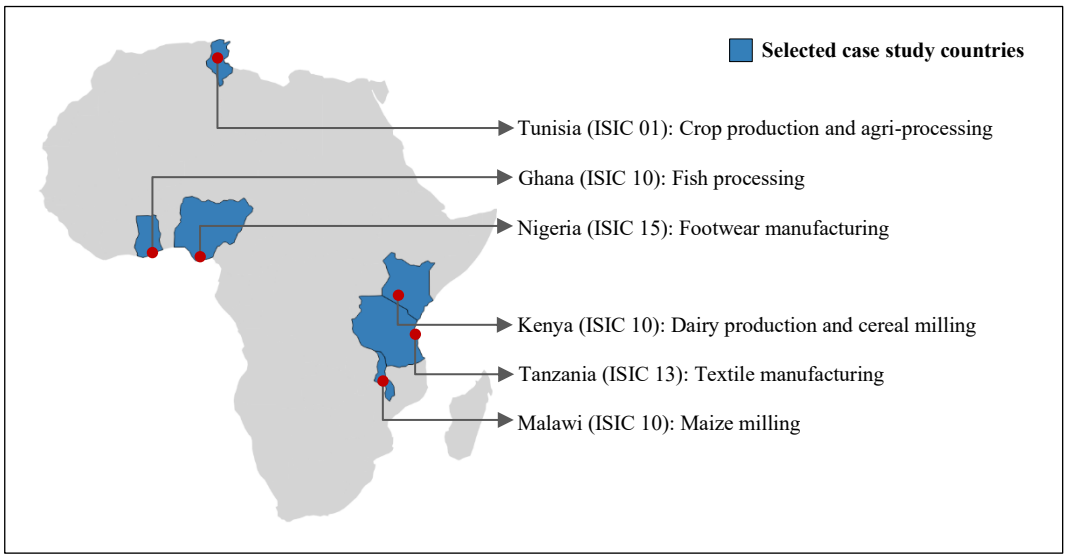

Figure 25. Overview of selected case studies

Notes: The Africa map was produced using QGIS (QGIS.org) with country boundary data from Natural Earth (naturalearthdata.com). The map shows the following countries (listed in alphabetical order): Ghana, Kenya, Malawi, Nigeria, Tanzania, and Tunisia. Red dots indicate the approximate locations of case study sites. Boundaries do not imply official endorsement or political recognition. The map is for illustrative purposes only.

Each case is built around a specific enterprise or enterprise cluster and evaluates multiple energy transition scenarios using predominantly the HOMER Pro software to simulate the performance of grid-connected and decentralised energy configurations. These include net-metered solar PV systems, stand-alone solar PV systems with battery storage, electric heat pumps, LPG-based thermal solutions, biomass waste-derived fuels and gases, and hybrid diesel-renewable combinations. Each scenario is assessed against core metrics, including system reliability, net present cost (NPC), capital expenditure (CAPEX), annual operating costs, and carbon dioxide equivalent ($CO_{2\text{-eq}}$) emissions.

The decision to include six cases was intentional and driven by both methodological and ethical considerations. During field engagement, participating entrepreneurs expressed strong interest in seeing how energy solutions could be applied in their local contexts. Representing each focus country (except Egypt, where the one assessed enterprise did not meet the selection criteria for this phase) allowed for a basic level of knowledge return to participants, enhancing the practical value of the research across geographies. In addition, the range of technologies modelled across the six cases captures meaningful variation in energy use patterns, infrastructure constraints, and sector-specific needs in food and textile

processing. While these case studies are not statistically representative and should not be generalised without contextual interpretation, they offer grounded, transferable examples of what energy transition pathways might look like for MSMEs operating under similar constraints. This diversity also strengthens the potential for peer learning, both within countries and across regions, by illustrating what is technically feasible, environmentally assessed, and financially modelled in comparable settings.

The methodological approach of this chapter is anchored in the World Bank's MTF, which serves both as a guide for selecting enterprises that exhibit low energy access performance and as a reference structure for assessing the potential improvements achieved through each scenario. While HOMER Pro simulations provide technical and economic outcomes, the MTF is applied to each enhanced scenario to quantitatively measure gains across energy access attributes. The environmental impact assessment of each scenario is evaluated using the Greenhouse Gas (GHG) Protocol, providing a consistent and standardised approach to emission accounting.

The chapter's results are structured in two major sections. The first section presents the individual techno-economic case study analyses, including detailed modelling of current baseline conditions and proposed enhanced configurations. These analyses incorporate environmental impact assessments to evaluate the carbon intensity of each solution. The second section reapplies the MTF to assess improvements in energy access performance under each enhanced configuration. This provides a structured way to understand the multidimensional benefits and limitations of each proposed intervention.

Taken together, the analysis in this chapter recognises that the modelled outcomes cannot be interpreted in isolation from broader systemic conditions. The scenarios are not proposed as standalone blueprints but as decision-support tools that must be embedded in enabling policy frameworks, inclusive financing mechanisms, and locally relevant institutional arrangements. These dimensions, crucial for real-world feasibility, will be the focus of Chapter 8, which assesses appropriate business models and financing strategies to support the adoption of clean energy interventions in women-owned enterprises across Africa.

7.2 Materials and methods

To operationalise the multi-method research approach for this part of the study, the following subsections present each methodological strand in detail. First, the World Bank's MTF is introduced as the conceptual and evaluative structure underpinning both case study selection and scenario assessment. Second, the techno-economic modelling approach using HOMER Pro is outlined, including supplemental calculations conducted in Excel where necessary. Third, the methodology for environmental impact assessment is detailed, drawing on the GHG Protocol to estimate greenhouse gas (GHG) emissions associated with each scenario. Together, these methods provide a structured, integrative foundation for analysing energy access improvements from technical, financial, and environmental perspectives.

To provide a high-level overview, Table 14 summarises the tools and indicators applied across each methodological strand.

Table 14. Overview of methods, tools, and key indicators used in the multi-method case study analysis

	Case study selection	**Techno-economic modelling**	**Environmental impact assessment**	**Evaluation of case study's enhancement scenarios**
Tool used	World Bank's MTF	HOMER Pro, complemented by Excel	GHG Protocol and PCAF	World Bank's MTF
Key indicator(s)	MTF score	NPC, CAPEX, O&M costs	GHG emissions ($CO_{2\text{-}eq}$), by scope	Change in MTF score per attribute
Purpose	Identify enterprises with lowest access levels and diverse energy needs	Assess cost-effectiveness and technical feasibility of clean energy systems	Estimate GHG emissions for each scenario	Evaluate energy access improvements under proposed energy interventions

Abbreviations: $CO_{2\text{-}eq}$ = carbon dioxide equivalent; GHG = greenhouse gas; HOMER Pro = Hybrid Optimization of Multiple Energy Resources Professional; MTF = Multi-Tier Framework; NPC =

net present cost; O&M = operation and maintenance; PCAF = Partnership for Carbon Accounting Financials

7.2.1 The World Bank's MTF as a conceptual and evaluative structure

Building on the empirical foundation established in Chapter 6, this part of the study draws on the previously assessed MTF results to identify a focused subset of enterprises for in-depth case study analysis. The MTF framework is then reapplied only at a later stage to evaluate how specific enhancement scenarios would improve energy access across the same set of attributes. This approach ensures methodological continuity while enabling a before-and-after comparison of energy access improvements at the enterprise level.

The process of selecting case studies involved identifying enterprises that met several key criteria. First, enterprises operating at tiers 1-3 were prioritised, as these have the most critical need for alternative energy solutions. Second, enterprises that utilised multiple energy carriers, such as electricity, thermal energy, mechanical power, and cooling, were given preference. This is an important aspect, as it reflects the more complex energy needs of productive use sectors, which are often under-researched (Pueyo, Bawakyillenuo, et al., 2020; Pueyo, Carreras, et al., 2020; Pueyo & Maestre, 2019). Third, to ensure a diverse sample, one enterprise was selected per country, ensuring that the case studies represented a broad geographical and sectoral spectrum. Egypt, however, was excluded, as the one enterprise audited did not meet the criteria for low energy access (tiers 1-3).

The final selection of six case studies spans Ghana, Kenya, Malawi, Nigeria, Tanzania, and Tunisia. Out of the six case studies, four represent food enterprises, and two are engaged in the textile sector. Specifically, three of the food enterprises fall under ISIC Division 10 (Manufacture of food products), with one classified as ISIC Division 1 (Crop and animal production, hunting, and related service activities). One textile enterprise is categorised as ISIC 15 (Manufacture of leather and related products), while the community-based case study is grouped under ISIC 13 (Manufacture of textiles). Only one enterprise, categorised under ISIC Division 10, operates completely off-grid with no grid extension expected soon.

The energy access levels of the MTF for the selected case studies reveal diverse challenges and opportunities across different sectors and geographies. **Case study 1**, a Ghanaian NGO involved in fish processing, scores the lowest with a final score of 1. This poor performance stems from multiple compounding factors: serious

health hazards associated with indoor frying and drying using charcoal and firewood, reliance on unregulated informal fuel suppliers, and the unreliability of the grid, which had previously caused a fire. **Case study 2**, a Tunisian agricultural entrepreneur, scores a final 2 with a major barrier being limited energy availability. Challenges include insufficient solar water pumping capacity to irrigate the entire farmland and reliance on an external olive oil processing facility, leading to high transportation costs and inconvenience. **Case study 3**, a Kenyan enterprise engaged in dairy and cereal milling, scores a 3. It uses multiple carriers, including grid electricity, solar PV, briquettes for thermal needs, and a diesel backup generator for critical dairy operations. Nevertheless, frequent grid outages and low performance in the health attribute, as defined by the World Bank methodology, persist as significant challenges. This is primarily due to the reliance on non-BLEENS energy carriers. BLEENS include biogas, liquefied petroleum gas, electricity, ethanol, natural gas, and solar, which are recognised as higher-tier energy carriers for their superior performance in meeting energy needs (Bhatia & Angelou, 2015). **Case study 4**, a Malawian informal enterprise operating two diesel-powered maize mills, also scores 3. The enterprise faces high fuel costs and downtime for repair and maintenance, compounded by health risks from diesel fumes. **Case study 5**, a Nigerian textile enterprise producing footwear, receives a score of 3. Frequent grid outages disrupt production, requiring reliance on backup generators, which presents logistical challenges due to occasional fuel shortages in the country. Finally, **case study 6**, a community initiative, assumes that 50 aspiring women entrepreneurs initially rely on energy carriers commonly available in Dar es Salaam, such as LPG, firewood, charcoal, and grid electricity, reflecting typical energy use patterns of urban households (Johnsen et al., 2015; National Bureau of Statistics & Statistics Norway, 2023). The productive use profiles for this group are modelled using the core entrepreneur, who initiated and supports this broader initiative, as a reference point. Based on this setup, case study 6 receives a tier 1 energy access score. This outcome is primarily driven by the use of charcoal and firewood for thermal demands. This contributes to poor health outcomes, elevated fuel costs (particularly for charcoal), and low scores under the legality attribute. The latter reflects the assumption that some fuel, especially charcoal and firewood, may be sourced from informal suppliers.

Figure 26 presents the energy access levels of each case study, evaluated across eight attributes of the MTF and distinguishing between electric and non-electric energy carriers. The case studies are ordered by their final scores, starting with the lowest-performing enterprise, case study 1 (Ghana, final score: 1). This is followed by case study 2 (Tunisia, final score: 2), case study 3 (Kenya, final score: 3), case

study 4 (Malawi, final score: 3), and case study 5 (Nigeria, final score: 3). Case study 6 (Tanzania, final score: 1) is presented last, as it represents a distinct case, a community-based initiative, rather than an individual enterprise.

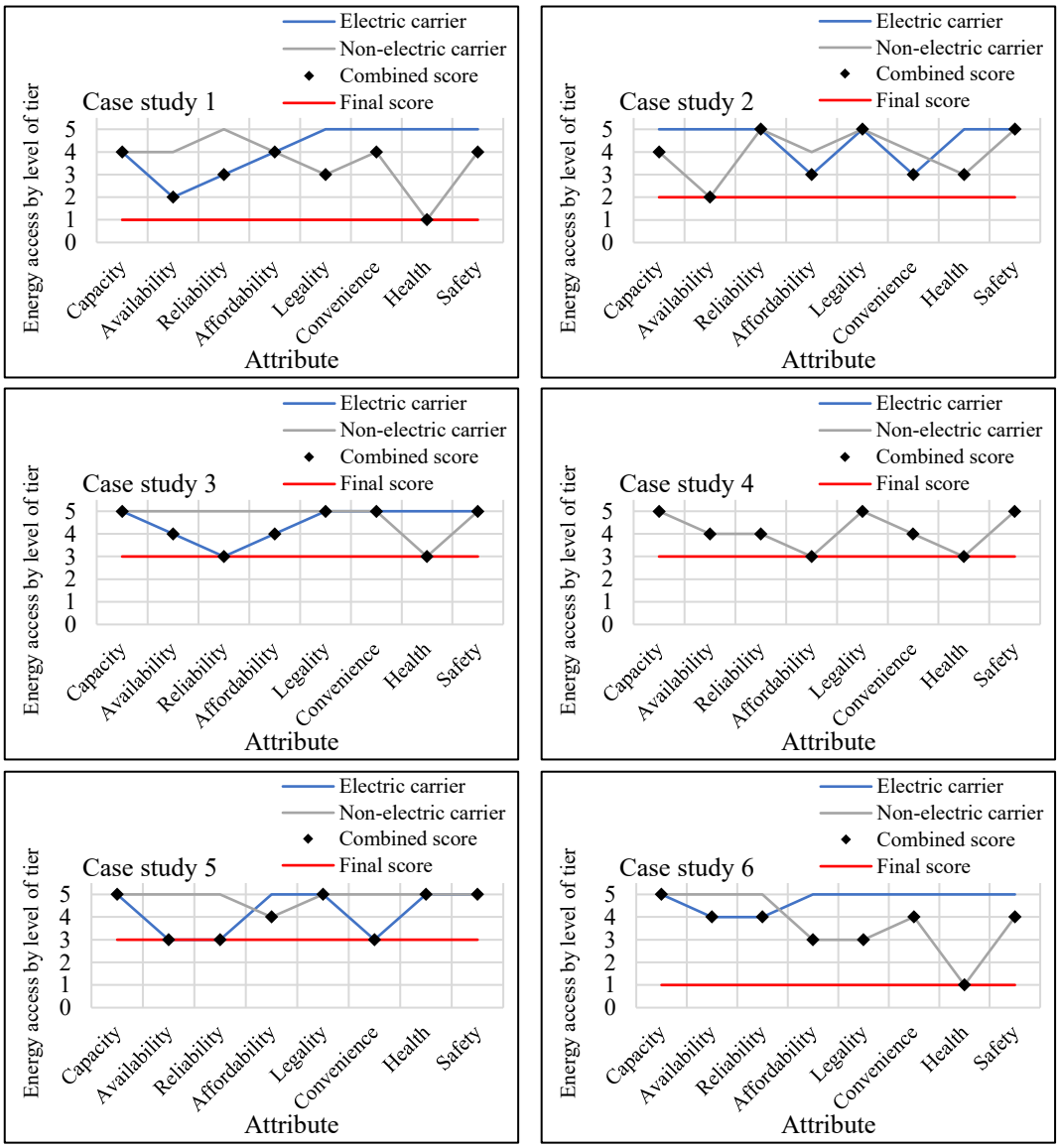

Figure 26. Energy access performance of each case study

Notes: The combined score for each attribute is determined by the lowest tier score assigned to either the electric or non-electric energy carrier. The final score for an enterprise is the lowest combined score across all attributes and energy carriers.

To maintain methodological consistency with Chapter 6, each enhancement scenario was assessed using the World Bank's MTF for productive energy applications. Each scenario's performance across the eight MTF attributes (i.e.,

capacity, availability, reliability, affordability, legality, convenience, health, and safety) was evaluated following the same tier assignment logic applied in Chapter 6. The tier scores are based on predefined thresholds from Bhatia & Angelou (2015), with minor adaptations where necessary. Scenario variants differing only by battery storage technology were consolidated, as such differences do not alter overall tier outcomes. Detailed scenario-specific assumptions and parameters used for tier allocation are provided in the respective case study section. This structure ensures that the impact of each intervention is grounded in both the MTF methodology and the practical realities of each enterprise.

7.2.2 HOMER Pro for techno-economic modelling

To evaluate the feasibility of clean energy system configurations for women-owned enterprises, this study adopted a techno-economic modelling approach anchored in HOMER Pro. As one of the most widely used energy system modelling tools, HOMER Pro enables the simulation, optimisation, and comparison of hybrid energy systems by balancing technical performance and economic viability (Lambert et al., 2005; UL Solutions, 2024). Its capacity to model systems combining renewable and conventional energy sources, such as solar PV, diesel generators, battery storage, and biomass, makes it particularly suited for decentralised and off-grid contexts common across the African continent.

Central to HOMER Pro's methodology is the simulation of hourly energy flows over a full annual cycle (Lambert et al., 2005). This time-series analysis evaluates how a system meets fluctuating energy demand under varying resource conditions, load patterns, and component interactions. The tool simulates both electric and thermal loads, allowing for a holistic assessment of enterprises whose operations depend on multi-carrier energy use. HOMER Pro then identifies the least-cost system configuration through optimisation routines, using either an exhaustive grid search or the more efficient HOMER Optimiser algorithm. The result is a ranked list of technically feasible and economically optimal system designs.

The core economic metric used in this study is the NPC, which captures the total discounted lifecycle cost of an energy system, including CAPEX, component replacements, operation and maintenance (O&M) costs, fuel or electricity purchases, and potential revenues from selling excess power (Lambert et al., 2005). It also deducts the salvage value of components, defined as the remaining value of a system element at the end of the project lifetime.

Alongside NPC, which serves as the principal metric for comparing system-level economics in HOMER Pro, two additional financial indicators were isolated, namely CAPEX and annual operating costs. These indicators reflect key decision-making constraints, upfront investment and ongoing financial burden. Annual operating costs are derived by subtracting the annualised share of CAPEX from the annualised NPC, isolating recurrent expenses such as fuel, maintenance, and repairs. Together, these metrics offer a clearer picture of end-user cost exposure over time.

To generate meaningful results, HOMER Pro requires a detailed set of inputs, broadly categorised as technical and economic parameters. On the technical side, load profiles were developed based on the energy audit findings for each enterprise, capturing hourly patterns of electricity and thermal demand (Gad & Leone, 2025). These were combined with location-specific solar resource data, drawn from HOMER's integrated databases via GPS coordinates. Component specifications were obtained from manufacturer data or, where unavailable, drawn from established literature.

The economic inputs included context-specific values for CAPEX, O&M, and replacement costs for all components, as well as country-specific fuel prices and applicable taxes. Discount rates[6] were adjusted to reflect local financing conditions and risk premiums. Grid tariffs were included for grid-connected scenarios.

A full overview of the technical and economic inputs used in HOMER Pro modelling is provided in Appendix D, while case-specific modelling assumptions are detailed in the corresponding sections for each enterprise scenario.

While HOMER Pro proved robust for simulating a wide range of configurations, its functionality was insufficient for certain case-specific parameters, particularly when integrating mixed energy carriers. To address these limitations, supplemental modelling was carried out in Microsoft Excel using equivalent equations and assumptions.

[6] This study uses country-specific nominal discount rates reported by Afful-Dadzie et al. (2022); Borgstein et al. (2019); Mas'ud et al. (2024); Odoi-Yorke & Woenagnon (2021); Osei et al. (2024); Saddari et al. (2025; Taylor et al. (2023); Zigah et al. (2023). A real discount rate would typically be derived by adjusting the nominal discount rate for the expected inflation rate. However, this adjustment was not made in the present assessment.

7.2.3 Environmental impact assessment

Complementing the techno-economic modelling, this study also includes an environmental impact assessment to evaluate the GHG emissions associated with each case study. This component is grounded in the Partnership for Carbon Accounting Financials (PCAF) framework (Partnership for Carbon Accounting Financials (PCAF), 2020, 2022), and builds on established methodologies from the GHG Protocol (Gómez & Watterson, 2006; Greenhouse Gas Protocol, 2024; United Nations Framework Convention on Climate Change (UNFCC) Secretariat, 2022). While PCAF was originally developed to support the disclosure of financed emissions by financial institutions, its principles, particularly the use of intensity-based metrics and the operational control approach, were adapted here to suit the specific context of women-owned MSMEs (PCAF, 2020, 2022).

Emissions were evaluated over a 25-year project horizon, with the assessment focusing exclusively on operational emissions rather than full life-cycle analysis. This approach excludes emissions from the manufacture, transport, or disposal of renewable energy systems, such as solar panels or batteries, consistent with the operational focus of this study (Gutsch & Leker, 2022; National Renewable Energy Laboratory (NREL), 2012). Following the GHG Protocol, emissions are categorised into scope 1 (direct emissions from fuel combustion), scope 2 (indirect emissions from purchased electricity), and scope 3 (other indirect emissions along the value chain) (UNFCC Secretariat, 2022).

The primary data for this assessment were collected through semi-structured face-to-face interviews with enterprise owners as presented in Chapter 6, enabling detailed characterisation of fuel consumption, electricity use, and business operations. Emissions were calculated using the Excel-based tool developed under the GHG Protocol (UNFCC Secretariat, 2022), which incorporates national grid emission factors and converts the seven Kyoto Protocol gases (i.e., CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, and NF_3) into $CO_{2\text{-eq}}$ using global warming potential (GWP) values from the Intergovernmental Panel on Climate Change (IPCC) (Greenhouse Gas Protocol, 2024). For traditional biomass-based fuels not included in the tool, additional GHG emission factors for CO_2, CH_4, and N_2O, and their corresponding GWP values, were applied as per IPCC guidelines (Gómez & Watterson, 2006; Greenhouse Gas Protocol, 2024). Table 15 presents the GHG emission factors by scope and subcategory for each country representing a case study.

Table 15. Summary of GHG emission factors by scope, subcategory, and country

Scope	Scope 1						Scope 2	Scope 3	
Sub-category	Energy carrier						Grid electricity	Business travel, land	
	Diesel	Petrol	LPG	Charcoal	Firewood	Sustainable biomass and gaseous biofuels[1]		Medium car	Large car
Ghana	2.55[a]	2.17[a]	1.56[a]	3.47[b]	1.89[b]	0[b]	0.36[c]	-	-
Kenya	2.55[a]	2.17[a]	1.56[a]	3.47[b]	1.89[b]	0[b]	0.32[c]	-	-
Malawi	2.55[a]	2.17[a]	1.56[a]	3.47[b]	1.89[b]	0[b]	0.04[c]	-	-
Nigeria	2.55[a]	2.17[a]	1.56[a]	3.47[b]	1.89[b]	0[b]	0.40[c]	-	-
Tanzania	2.55[a]	2.17[a]	1.56[a]	3.47[b]	1.89[b]	0[b]	0.48[c]	-	0.20[d]
Tunisia	2.55[a]	2.17[a]	1.56[a]	3.47[b]	1.89[b]	0[b]	0.40[c]	0.18[d]	0.22[d]

Notes:

[1]*Sustainable biomass, often referred to as modern biomass (as opposed to traditional biomass), encompasses organic materials, derived from sustainably managed plant, animal, and waste sources, that are used for energy end-use applications, predominantly in liquid or gaseous form (Chum et al., 2011). Sustainable biomass is processed or upgraded to serve as a more efficient secondary energy carrier, such as briquettes and coconut husks (solid fuels) or converted via biochemical and thermochemical processes into gaseous biofuels like biogas, biomethane, and syngas, as considered in this study.*

[a]*$kgCO_{2\text{-}eq}$/L, based on UNFCC Secretariat (2021).*

[b]*$kgCO_{2\text{-}eq}$/kg, based on emissions of CO_2, CH_4, and N_2O, with emission factors derived from IPCC* (Gómez & Watterson, 2006) *and global warming potentials (GWPs) taken from the IPCC's Sixth Assessment Report (AR6) (Greenhouse Gas Protocol, 2024). For charcoal and firewood, the analysis assumes non-sustainable biomass use, meaning that the carbon emitted during the combustion of charcoal and firewood is not offset by regrowth or sustainable management practices. GHG emissions from sustainable biomass sources, including briquettes, coconut husks, and gaseous biofuels such as biomethane, biogas, and syngas derived from sustainable biomass, are considered carbon-neutral. This assumption is based on the closed carbon cycle concept for short-term biogenic*

materials, wherein the CO_2 released during combustion is reabsorbed by the regrowing biomass. Other GHG emissions, such as methane (CH_4) and nitrous oxide (N_2O), are excluded from this assessment for these energy carriers (Rypdal & Paciornik, 2006).

[c] *$kgCO_{2\text{-}eq}$/kWh, based on UNFCC Secretariat (2021).*

[d] *$kgCO_{2\text{-}eq}$/km, based on the assumption that the vehicle fuel in Tunisia is unknown, while in Tanzania diesel is assumed as vehicle fuel (UNFCC Secretariat, 2022).*

To define the organisational boundaries for emissions reporting, the operational control approach was selected among the three options recommended by PCAF, equity share, financial control, and operational control (PCAF, 2020, 2022). This approach was best aligned with the nature of the enterprises studied, which are fully controlled by their owners or NGO-based stakeholders. Under this model, 100% of emissions are attributed to the enterprise when it holds operational control.

To enhance comparability across enterprises, the study adopted an emissions intensity metric, reporting emissions per tonne of production ($tCO_{2\text{-}eq}$/tonne), consistent with PCAF recommendations (PCAF, 2020, 2022). This metric offers additional insight into the environmental efficiency of enterprises across different sectors and energy configurations.

Together with the HOMER Pro modelling, this environmental assessment forms an integrated methodological framework for evaluating both the techno-economic and environmental viability of enhanced energy access scenarios.

7.3 Results

This chapter offers an in-depth analysis of the energy-related challenges encountered by the assessed case studies and proposes context-specific, renewable energy solutions to improve the operational performance and sustainability within women-owned enterprises. Each case study is presented individually and follows a three-part structure to ensure analytical consistency and comparability across enterprises.

The first section provides a contextual overview of the base case, drawing on data collected through structured face-to-face interviews and direct assessments of production processes. It outlines the enterprise's operational background, energy access conditions, existing techno-economic configuration, and current environmental footprint. To facilitate meaningful cross-case comparison, all reported energy use data were standardised into kWh. This conversion was carried out using LHV, energy carrier densities (where applicable), and assumed end-use

efficiencies based on appliance type and fuel source. The harmonisation approach, consistent with that adopted in Chapter 5, ensures comparability across different energy carriers and usage contexts. The specific parameters and conversion factors used are detailed in Appendix B. Readers seeking additional insights can consult the accompanying technical dataset, which presents comprehensive energy consumption profiles (Gad & Leone, 2025).

The second section models a range of renewable energy system configurations tailored to each case study. Using HOMER Pro as the primary tool for techno-economic scenario analysis, the study evaluates system performance, financial feasibility, and associated GHG emissions for each configuration. Where the software's scope proved insufficient, complementary modelling was conducted in Excel. This hybrid approach ensures greater accuracy and customisation in determining optimal energy solutions.

Finally, the third section revisits the MTF to assess how each proposed scenario alters the level and quality of energy access. By comparing baseline and enhanced conditions across the eight MTF attributes, this section highlights the extent to which renewable energy interventions can improve service delivery, affordability, and environmental sustainability for women-owned micro- and small-sized enterprises.

7.3.1 Case study 1: Ghana – Fish processing

Located in Kokrobite (Accra), Ghana, this micro-sized NGO integrates both social and commercial activities, processing approximately 203 kg of fish per month with a profit margin of 25%. The organisation is governed by a board comprising both male and female members and has a strong focus on community engagement. One of its key initiatives is a sanitation unit that provides training and capacity building on fish cleaning and brining prior to processing into smoked fish. This unit generates minimal fish waste of approximately 0.5 kg/day, which is directly discharged into underground pipes, rendering it inaccessible for any potential waste treatment or waste-to-energy application. The sanitation unit is powered by a solar PV system financed by the United States Agency for International Development (USAID); however, it will not be included in the present case study assessment. The focus of this analysis is the productive use unit, which processes cleaned, cut, brined, and pre-dried (sun-dried) fish into smoked fish. This unit serves both the local community, which utilises its services for a processing fee, and the NGO itself, which sells the processed fish to sustain its operations.

Processing activities take place in a sheltered facility and include key operations such as freezing, mixing, milling, drying, frying, and smoking.

One of the female shareholders cites key challenges such as securing funding, limited availability of raw fish for processing, and rising fuel costs. Additionally, customer resistance to paying higher processing fees limits profitability amidst increasing operational expenses. Gender-related challenges include navigating gender-biased attitudes and asserting herself among male colleagues. However, she notes that improving societal awareness of gender equality has made this aspect more manageable.

Motivations for adopting renewable energy include environmental sustainability. However, the shareholder lacks knowledge about renewable options and has yet to discuss such investments with the other shareholders. Her willingness to invest aligns with the NGO's current energy expenditure, estimated at around 50 USD/month.

Applying the World Bank's MTF, the NGO achieves an overall energy access score of 1. The reliance on non-electric energy carriers like charcoal and firewood for indoor activities presents severe health risks and operational inefficiencies. Furthermore, a fire accident, triggered by fuel combustion in the kilns, damaged the electrical infrastructure, resulting in a complete loss of grid supply for an extended period. Even before this incident, frequent power outages had already disrupted electricity-dependent operations during normal grid conditions.

This overview sets the scene for a deeper examination of the enterprise's current energy landscape. The following section presents the base case analysis, detailing the NGO's existing energy access conditions, the techno-economic configuration of its energy systems, and the environmental implications of its current operations. By doing so, it provides the foundational benchmark against which the viability and impact of proposed enhancement scenarios will be assessed.

7.3.1.1 Base case

The base case of this case study focuses on the fish smoking processing facility, which utilises cleaned, cut, brined, and occasionally sun-dried fish as input for further processing.

While sun-drying is not systematically practised, open-air fish drying through direct sun exposure occasionally serves as a preliminary step before further processing into smoked and fried fish. When utilised, it is typically conducted for an average of 5 hours/day over 2 days/month. The drying process may involve salting or fermentation prior to sun exposure, depending on the specific requirements of the end consumers. In general, sun drying is a widely adopted technique due to its cost-effectiveness, as it requires no significant infrastructure or operational expenses (Al-Mashruqi & Al-Ismaili, 2021). By placing the fish in an open space, solar radiation increases its temperature, facilitating moisture reduction. This method also contributes to reducing overall fuel consumption by decreasing the need for subsequent thermal processing using LPG, charcoal, or firewood. Despite its advantages, open-air sun drying presents several challenges, including dependence on weather conditions, the need for extensive drying areas, prolonged processing times, and relatively low drying rates (Al-Mashruqi & Al-Ismaili, 2021; Babiker et al., 2024). Additionally, it poses risks such as contamination from dust and foreign materials, and exposure to microorganisms, insects, and other animals. Although open-air sun drying currently plays a minimal role in the overall processing chain by reducing moisture content and lowering subsequent thermal energy requirements, it does not involve any technological infrastructure, energy carrier, or direct economic cost. As a result, it is not explicitly accounted for in the base case analysis, which focuses on energy-consuming processes with measurable economic and technical components.

The processing facility of the NGO relies on grid electricity for three key operations: freezing, milling and mixing. Freezing is used both as a pre-treatment step immediately after cleaning and as an intermediate storage method to accommodate the batch-processing workflow. Milling and mixing, on the other hand, serve as a final processing step, occurring after the fish has been smoked and cooled down. Thermal energy for smoking is supplied using LPG, charcoal, and firewood, which feed three different kilns. The selection of kiln and corresponding fuel is largely influenced by cost and availability, reflecting the practical trade-offs faced by the NGO. LPG is reported to be the most practical option, as it enables continuous kiln operation for up to 24 hours with minimal supervision. In contrast, charcoal and firewood kilns can only be operated during working hours and require constant oversight and manual handling, but are perceived as the more cost-effective alternative to LPG. On average, the total energy expenditure amounts to 53 USD/month and accounts for 8% of the NGO’s total expenses.

The temperature requirements for thermal processes vary considerably: Frying operations demand high heat inputs, reaching up to 190 °C, whereas drying and smoking processes typically occur at lower temperatures, generally below 100 °C. In contrast, freezing requires a controlled cold environment, maintained at approximately -18 °C to ensure food preservation and safety. Table 16 summarises the key productive use applications of this case study.

Table 16. Case study 1: Summary of productive use applications

Process	Temperature	Energy carrier	Appliance		Power rating or consumption	
	°C	Type	Count	Type	Value	Unit
Drying; Smoking	90; 30-40	LPG	1	Kiln	7.8	L/month
Drying; Smoking	85; 30-40	Charcoal	1	Kiln	43.3	kg/month
Drying; Smoking	85; 30-40	Firewood	1	Kiln	120	kg/month
Freezing	-18	Grid electricity	2	Freezer	0.26	kW
Frying	175-190	LPG	1	Stove	9.4	L/month
Milling	-	Grid electricity	1	Mill	0.2	kW
Mixing	-	Grid electricity	1	Mixer	0.2	kW

Abbreviations: °C = degree Celsius; kg = kilogramme; kW = kilowatt; L = litre; LPG = liquified petroleum gas

Understanding the thermal and electrical processes involved provides a basis for estimating the enterprise's daily energy demand profile. While sun-drying plays a marginal role and is excluded from the base case due to its non-energy-intensive nature, the remaining operations, freezing, milling, mixing, frying, and smoking,

exhibit defined operational patterns with measurable energy requirements. These processes differ not only in energy carrier type (electricity vs. thermal fuels) but also in timing, intensity, and frequency of use. By analysing equipment specifications, reported usage hours, and monthly fuel consumption, a representative daily demand schedule can be constructed. The main techno-economic parameters and assumptions can be accessed in Appendix D.

The fish smoking facility operates five days a week. Two freezers run continuously throughout the year. However, since refrigerators cycle on and off to maintain internal temperatures, their estimated power requirement of 255 W corresponds to the compressor's active cycle rather than continuous operation (Bhatia & Angelou, 2015). Although plugged in 24 hours a day, it is assumed that the compressor operates for approximately 5 hours per day (Bhatia & Angelou, 2015). The mixer (0.2 kW) operates for three hours daily, from 12:00 to 15:00, five days a week. The milling device (0.2 kW) is powered by the grid for 1h/day, 5 days/week, typically at 15:00. The total annual electricity demand amounts to approximately 871 kWh/year.

For all thermal energy appliances, including the LPG stove and the three kiln types, peak thermal demand was estimated by dividing total monthly energy consumption by the number of operating hours per month, based on reported usage schedules. This approach ensures that the peak load reflects the actual intensity of use during active operation periods, rather than averaged consumption over time.

The LPG stove for frying is used intermittently, averaging 2 hours/day for 4 days/month. For modelling purposes, it is assumed to be in operation between 12:00 and 14:00. This results in an annual LPG consumption of approximately 113 L/year, corresponding to a final energy demand of 449 kWh/year, based on an LHV of 47.3 MJ/kg, a density of 0.53 kg/L and a stove efficiency of 57% (Garg et al., 2006; Islam et al., 2022; Shen et al., 2018; Statistics Netherlands, 2025). With an assumed lifetime of 10 years (Mindjimba, 2020), the replacement cost for the LPG cookstove is estimated at 75 USD/unit, a global average value according to the Organization of the Petroleum Exporting Countries (OPEC) Fund for International Development (2024). The value is in line with the cost of energy-efficient cookstoves distributed in Senegal, varying between 39 and 105 USD/unit (Bensch et al., 2024) and comparable to LPG cookstoves in Tanzania with a cost of 66 USD/unit (The United Republic of Tanzania & Ministry of Energy, 2024).

The LPG kiln operates 4 days/month, running continuously for 24 hours per day during those periods, as production is conducted in bulk rather than consistently throughout the month. This results in an annual LPG consumption of 94 L/year, equivalent to 374 kWh/year. It is assumed that the LPG kiln requires replacement every 10 years (Shaik et al., 2022), with an investment of approximately 74 USD/unit/replacement cycle. This covers the structural components (such as bricks, sand, and clay), 30% of the costs attributed to unskilled labour required for building and constructing the kiln, and the interior components, including gas-related equipment (Nyemah & Rotawewa, 2021; Ogundana et al., 2022). All cost components are scaled to kiln size based on daily production capacity.

Charcoal and firewood kilns, in contrast, are used during working hours between 9:00 and 17:00, also 4 days/month. The annual charcoal consumption is estimated at 520 kg/year, corresponding to 937 kWh/year, while firewood consumption amounts to 1,440 kg/year, or 1,373 kWh/year. These values are based on LHV of 29.5 MJ/kg for charcoal and 15.6 MJ/kg for firewood, with appliance efficiencies of 22% (Ballard-Tremeer & Jawurek, 1996; Ekouedjen et al., 2020; Garg et al., 2006). Similar to the LPG kiln, the charcoal and firewood kilns are estimated to have a lifespan of 10 years (Mindjimba, 2020; Shaik et al., 2022). While requiring the same structural and labour costs as the LPG kiln, they do not involve gas-related components, leading to lower replacement expenses of approximately 41 USD/unit/replacement cycle. This cost estimate aligns with the assessments made by the Food and Agriculture Organization of the United Nations (FAO) from Côte d'Ivoire, where Chorkor[7] kilns, an improved version of traditional kilns, are valued at approximately 50 USD/unit (Mindjimba, 2020). Comparable costs are given from a study in South Sudan for Chorkor kilns, including construction materials, labour, and interior components such as racks and furnaces (Mondo et al., 2021). Since Chorkor kilns typically operate on charcoal or other biomass-based fuels, these estimates provide a relevant cost benchmark for the kilns in this case study (Ajang et al., 2010; Mindjimba, 2020; Mondo et al., 2021; Ndiaye et al., 2015). Similar to the LPG kiln, the cost estimates for the charcoal and firewood kilns are linearly scaled based on daily production capacity.

[7] The Chorkor kiln, named after the fishing community of Chorkor near Accra, Ghana, was developed in 1969 by the Food Research Institute (FRI) in collaboration with local women fish processors (Ndiaye et al., 2015). Later promoted by the FAO, it aimed to enhance fish smoking quality, reduce post-harvest losses, and improve working conditions. Primarily designed for smoking, the kiln can also be used for drying and storing processed fish.

Although the replacement cost assumptions are based on kiln and stove technologies used in various developing countries, including Nigeria, Côte d'Ivoire, Senegal, South Sudan, and the Federated States of Micronesia, which differ in socio-economic and geographic contexts, the similarities in small-scale fish processing techniques, kiln construction materials, and operational conditions suggest that the cost and lifespan estimates are reasonably applicable for Ghana. Furthermore, the durability and maintenance requirements of kilns and stoves are generally consistent across regions with similar fuel availability, processing demands, and construction practices, which strengthens the reliability of these assumptions. The complete technical setup is illustrated in Figure 27.

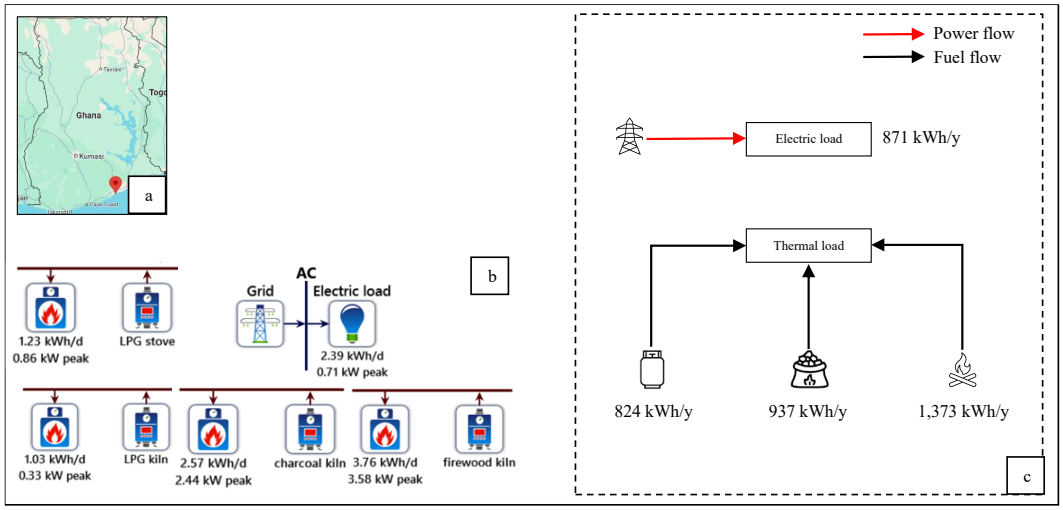

Figure 27. Case study 1: Technical setup of the base case

Notes: a) Geographic location, source: google.maps; (b) Technical setup designed using HOMER Pro; c) Summary of technical setup including electric and thermal demand by type of energy carrier.

Abbreviations: kW = kilowatt; kWh/d = kilowatt-hour per day; kWh/y = kilowatt-hour per year; LPG = liquified petroleum gas

Assuming a nominal discount rate of 10% and a project lifetime of 25 years, values commonly cited in the literature for renewable energy projects in Ghana (Afful-Dadzie et al., 2022; Odoi-Yorke & Woenagnon, 2021; Osei et al., 2024; Saddari et al., 2025) the base case results in an NPC of 5,678 USD, with annual operating costs amounting to 626 USD/year. Fuel and grid electricity expenditure accounts for almost all (98%) of total NPC, with LPG and charcoal each contributing 29%, while firewood and grid electricity make up 21% and 19%, respectively. Replacement costs for kilns and stoves together represent around 2%

of the NPC. A detailed breakdown by energy carrier and replacement costs is presented in Table 17.

Table 17. Case study 1: Net present cost and operating costs of the base case

Component	NPC (USD)	Operating costs (USD/year)	Share of NPC (%)
Energy carrier			
Grid electricity	1,073	118	19%
LPG	1,647	182	29%
Charcoal	1,647	182	29%
Firewood	1,186	131	21%
Replacement costs			
Kilns	84	9	<2%
Stove	40	4	<1%
Total	**5,678**	**626**	**100%**

Notes: A nominal discount rate of 10% is applied, and the project lifetime is set for 25 years. Due to rounding, the sum of individual items may not exactly match the total.

Abbreviations: % = percent; LPG = liquified petroleum gas; NPC = net present cost; O&M = operation and maintenance; USD = United States dollar

The reliance on multiple energy carriers in this case study, commonly referred to as fuel stacking, not only reflects practical trade-offs around cost, reliability, and availability but also signals deeper structural constraints within the energy ecosystem. While this approach allows for operational flexibility, it often comes at the expense of environmental and health sustainability. In particular, the continued dependence on charcoal and firewood, fuels frequently chosen for their

affordability and accessibility, raises serious concerns. Unsustainably sourced biomass contributes to deforestation and ecosystem degradation, while its combustion in poorly ventilated spaces exposes workers to harmful levels of indoor air pollution, elevating long-term health risks (Asiedu et al., 2018; Bensch et al., 2024; Kwofie et al., 2019; Mindjimba, 2020).

To better understand the broader implications of these energy choices, an environmental impact assessment was conducted. This analysis quantifies direct (scope 1) and indirect (scope 2) GHG emissions associated with current operations, following the internationally recognised methodologies of the GHG Protocol, IPCC, and PCAF (Gómez & Watterson, 2006; Greenhouse Gas Protocol, 2024; PCAF, 2020, 2022; UNFCC Secretariat, 2022).

It is estimated that the total emissions under current operation conditions amount to 5.16 $tCO_{2\text{-}eq}$/year, leading to a cumulative 129 $tCO_{2\text{-}eq}$ over the 25-year project lifetime, equivalent to 2.12 $tCO_{2\text{-}eq}$ per tonne of produced goods. The vast majority (94%) of emissions originate from scope 1 fuel combustion, while scope 2 emissions from grid electricity account for only 6% of the total. Within scope 1, firewood combustion emerges as the most significant source, contributing 56% of emissions, followed by charcoal at 37%, with LPG use responsible for the remaining 7%.

These findings highlight the substantial environmental and health burdens associated with traditional biomass reliance, reinforcing the urgency for cleaner and more efficient energy solutions. Addressing these challenges requires a shift toward low-emission alternatives and technological improvements, which will be explored in the following sections.

7.3.1.2 Scenario analysis

The scenario analysis for the Ghanaian case study examines strategies to improve the energy efficiency and sustainability of the NGO's fish processing operations while preserving product taste and quality, key factors essential to meeting customer preferences and market demands (Ajang et al., 2010; Ogundana et al., 2022). A key transition across all scenarios is the shift away from traditional smoking methods, including firewood, which exposes processors to harmful smoke, increasing the risk of respiratory and eye illnesses and long-term cancer susceptibility (Asiedu et al., 2018; Ndiaye et al., 2015). Conventional smoking also produces high levels of polycyclic aromatic hydrocarbons (PAHs), known

carcinogens. For instance, the International Association of Food Inspectors (IAFI) reported in 2017 that traditional West African smoked fish contained PAH levels of 32 ppb/kg, far exceeding EU food safety limits of 2 ppb/kg for benzo[a]pyrene and 12 ppb/kg for the four key PAHs (Asiedu et al., 2018; Mindjimba, 2020). Compliance with these standards is essential for market expansion, particularly for enterprises considering export opportunities, as is the case for the NGO under assessment. To address this, scenarios 1 and 2 transition entirely to LPG for thermal energy, while scenario 3 replaces LPG with a biomass-based fuel and integrates an improved kiln, the so-called Thiaroye Processing Technique (FTT), aligning with FAO recommendations.

Another common improvement across all scenarios is the introduction of a pre-smoking greenhouse dryer. While currently a minor step in the processing chain, sun drying reduces moisture content before smoking, lowering the thermal energy demand for subsequent processing. However, the current technique of open-air drying has several limitations: it relies entirely on ambient conditions, leads to significant product losses (30-40%) due to weather, contamination, and animal consumption, and is time-consuming while exposing the product to insect infestation, compromising hygiene and quality (Al-Mashruqi & Al-Ismaili, 2021). Implementing a simple greenhouse dryer offers a cost-effective solution to mitigate these issues, enhancing sanitary conditions, improving drying efficiency, and ensuring greater consistency in the smoking process (Al-Mashruqi & Al-Ismaili, 2021; Mustapha et al., 2014). More advanced solar drying technologies, such as forced convection or indirect solar drying, were not considered, as they are primarily designed for cases where drying itself serves as the primary preservation method (Al-Mashruqi & Al-Ismaili, 2021). Some studies have explored the integration of advanced solar drying with fuel-based smoking, demonstrating potential benefits such as improved operational efficiency, reduced fuel consumption, and shorter processing times (Nwakuba, 2016). While this approach presents an interesting avenue for future research, it falls outside the scope of this study, which remains focused on optimising the fish-smoking process (Mindjimba, 2020; Ndiaye et al., 2015; Nyemah & Rotawewa, 2021). Instead, the greenhouse dryer serves as a practical pre-smoking solution, improving hygiene and reducing losses, which aligns with the NGO's business model and supports its primary focus on fish smoking. The cost of a greenhouse dryer across all enhancement scenarios is estimated at approximately 160 USD per unit, representing an average across a range of available technologies (Mustapha et al., 2014). This includes simpler designs, such as net-covered frameworks, as well as more advanced systems incorporating glass housing and improved insulation. Rather than selecting a

specific technology, this average value is used to reflect a general market estimate. The assumed operational lifespan of the dryer is 10 years, aligning with typical durability reported in the literature for small- to medium-scale systems (Mustapha et al., 2014).

Scenario 1 introduces solar PV with net metering to offset electricity costs by feeding excess solar generation into the grid. The existing fuel mix for the thermal energy supply is replaced entirely with LPG for both frying and smoking. Scenario 2 builds on scenario 1 by replacing grid electricity entirely with solar PV and battery storage while maintaining LPG for frying and smoking. Two variations are considered: Scenario 2A utilises lead-acid batteries, whereas scenario 2B adopts lithium-ion batteries. The comparison assesses efficiency, lifespan, and cost-effectiveness to provide a comprehensive evaluation of energy self-sufficiency trade-offs. Scenario 3 adopts the different configurations of electrical energy supply introduced in scenarios 1, 2A and 2B while maintaining a consistent thermal energy setup. Across all the sub-scenarios of scenario 3, fish smoking is conducted using kilns based on the FAO-Thiaroye Processing Technique (FAO-FTT)[8], fuelled by coconut husks, while LPG remains the primary fuel for frying. The key distinction lies in the electricity supply: scenario 3A pairs FAO-FTT kilns with solar PV and lead-acid battery storage, scenario 3B substitutes lead-acid with lithium-ion batteries, and scenario 3C integrates a net metering system instead of battery storage. This structure allows for a direct comparison of battery technologies and net metering while ensuring a uniform transition to FAO-FTT kilns for fish smoking.

Scenario 1: Solar PV with net metering and LPG for thermal demand

Net metering remains in its nascent stages across many African countries, with its absence acting as a significant barrier to the advancement of increasing renewable energy supply (Afonaa-Mensah et al., 2024; Peprah, Aboagye, et al., 2023; Peprah, Gyamfi, et al., 2023). Addressing this gap is crucial for unlocking the continent's renewable energy potential. In Ghana, however, some progress has been made in implementing net metering, with policies and tariff structures now available for both residential and non-residential consumers (Energy Commission, 2023; Ghana Gazette & PURC, 2024; PURC, 2022). The government has taken

[8] The FAO-FTT is a fish-smoking technology developed in 2015 by FAO and the National Training Centre for Fisheries and Aquaculture Technicians (CNFTPA) in Senegal to improve combustion efficiency, reduce health risks, and ensure compliance with food safety standards (Ndiaye et al., 2015; Nyemah & Rotawewa, 2021).

steps such as enacting renewable energy laws, piloting net meters with solar PV systems, and introducing a regulatory framework to promote green distributed generation (Afonaa-Mensah et al., 2024). Despite these efforts, challenges persist, including price distortions, high electricity tariffs, differential pricing, and cross-subsidisation.

Under Ghana's net metering framework, each kWh exported to the grid beyond a customer's consumption earns a credit of 1 kWh within the billing period (PURC, 2022). Excess kWh credits can be carried forward to subsequent billing periods but expire at the end of the calendar year. However, net metering is not designed as a profit-generating mechanism. The maximum generating capacity per customer is limited to 500 kW, and distribution utilities are responsible for providing and maintaining the necessary equipment for bi-directional electricity flow.

In scenario 1, solar PV with net metering is introduced, while thermal energy demands are met using LPG. The shift in this scenario from charcoal and firewood to LPG does not present significant operational challenges, as these biomass fuels are primarily fuel-stacked due to their relatively lower costs rather than functional necessity (Gad & Leone, 2025). In practice, LPG is the preferred energy source for fish smoking, particularly as the NGO targets export markets, ensuring a consistent product quality that meets regulatory standards. Moreover, LPG offers greater convenience and efficiency, as kilns can operate continuously for 24 hours with minimal oversight, unlike charcoal and firewood, which require constant monitoring and manual intervention during working hours. Based on LHV, fuel density, and appliance efficiency (Garg et al., 2006; Islam et al., 2022; Shen et al., 2018; Statistics Netherlands, 2025), an annual requirement of 790 L/year of LPG is estimated to meet the necessary 3,134 kWh/year of thermal energy demand. It is assumed, as in the base case, that LPG will be used for 4 days/month, operating continuously for 24 hours on those days, maintaining the same productive use practices to ensure consistency in energy demand estimation. Meanwhile, the electrical demand is covered by solar PV and grid supply through the net metering scheme, without battery storage. All excess electricity generated is fed into the grid, and the grid supplies the necessary demand when solar energy is unavailable.

The Public Utilities Regulatory Commission (PURC) has defined net metering tariffs based on different scenarios, distinguishing between cases where imports (purchase) and exports (sale) are equal or where one exceeds the other (PURC, 2022). In this analysis, the category for non-residential users with higher exports than imports is applied. According to simulations using HOMER Pro, a 1 kW_p solar

PV system results in an annual purchase of 551 kWh/year from the grid while selling 1,057 kWh/year. The applicable tariff structure involves multiplying the capacity charge by the electricity purchased, subtracting the net exported electricity multiplied by the energy charge, and adding the service charge, along with levies and taxes. The exact values used are presented in Appendix D.

To enable net metering, a bi-directional meter is required, which is assumed to cost between 190-365 USD per unit, depending on whether a single-phase or three-phase system is used (Roux & Shanker, 2018). It is assumed that no replacement is required for such a bi-directional meter during the duration of the project. Regarding the CAPEX of the solar PV system, data from ESMAP was used as a reference. The module and inverter costs were estimated at 798 USD/kW_p (ESMAP, 2022). Literature indicates that these components typically account for 50-60% of total CAPEX in Ghana (Afonaa-Mensah et al., 2024; Aguilar, 2015). Assuming a conservative estimate of 50%, the total CAPEX for the system was extrapolated to 1,596 USD/kW_p, aligning with a cost breakdown of USD 0.70/W_p for modules, USD 0.202/W_p for inverters, and additional expenses based on scientific literature on solar PV costs in Ghana (Afonaa-Mensah et al., 2024; Aguilar, 2015). The complete technical setup is illustrated in Figure 28.

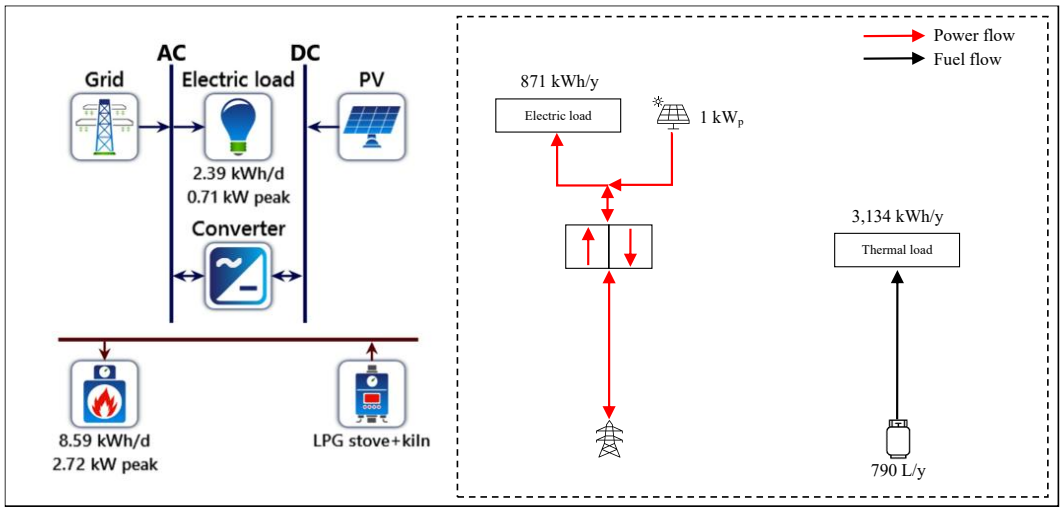

Figure 28. Case study 1: Technical setup of scenario 1

Notes: The left graphic was modelled with HOMER Pro, and the right graphic was modelled by the author.

Abbreviations: kW = kilowatt; kWh/d = kilowatt-hour per day; kW_p = kilowatt peak; kWh/y = kilowatt-hour per year; LPG = liquified petroleum gas; PV = photovoltaic

In this scenario, thermal energy demand is fully met by LPG, while the electricity demand of 871 kWh/year is supplied 27% by solar PV, with approximately 551 kWh/year sourced from the grid. This shows that despite the relatively small installed PV capacity, the model achieves a 27% renewable energy fraction. The system is designed to ensure that all excess electricity generated by the 1 kW_p solar PV system and 1 kW inverter is fed back into the grid, resulting in zero curtailments of solar electricity. Additionally, the system meets the entire electrical demand without any unmet load.

From an economic perspective, assuming a 10% discount rate and a 25-year project lifetime, the transition to LPG and solar PV results in a 59% increase NPC and a 28% increase in annual operating costs compared to the base case. The NPC rises to 9,032 USD, while annual operating costs amount to 802 USD/year. Unlike the base case, where costs were primarily driven by fuel and grid electricity purchases, this scenario introduces additional CAPEX for the solar PV system (18% of NPC), alongside increased LPG use, which now accounts for 69% of the NPC. Grid costs are significantly reduced, representing only 4% of the total NPC, with the remaining minor costs stemming from the bidirectional meter, greenhouse dryer, O&M, and replacement costs associated with the kilns, stove, and inverter.

The environmental impact is significantly reduced in this scenario, with a 72% decrease in GHG emissions compared to the base case. The majority of emissions, 86%, stem from scope 1 emissions due to LPG combustion, while the remaining 14% originate from scope 2 emissions associated with grid electricity use, which were calculated using a conservative approach, where emissions are based on total grid electricity purchased rather than net electricity (imported minus exported), ensuring alignment with GHG Protocol guidelines (Sotos, 2016). This transition highlights the substantial environmental benefits of shifting away from traditional biomass fuels while integrating solar PV for partial electricity supply.

Scenario 2: Solar PV with battery storage for grid independence and LPG for thermal demand

While the thermal energy demand remains unchanged, with the NGO continuing to use LPG for frying and smoking fish, scenario 2 explores the replacement of grid electricity with solar PV and battery storage. This scenario builds upon scenario 1, which already incorporated a solar PV system but relied on net metering to feed excess electricity back into the grid. In contrast, scenario 2 aims for complete grid independence by integrating battery storage. Two sub-

scenarios were modelled, differing in the type of battery technology employed: scenario 2A utilises lead-acid batteries, while scenario 2B adopts lithium-ion batteries.

The CAPEX assumptions for the solar PV system remain consistent with scenario 1. For lead-acid batteries, an average cost of 143 USD/kWh is used, based on ESMAP data for Ghana, whereas lithium-ion battery costs are assumed to be 455 USD/kWh, derived from ESMAP averages for the Africa/Asia region, as there is no data available specifically for Ghana (ESMAP, 2022). In terms of lifespan, the literature typically defines battery longevity in terms of energy throughput. Lead-acid batteries have an estimated lifespan of approximately 800 kWh of throughput, with a maximum depth of discharge of 60% and an efficiency of 80%, resulting in a usable energy output of 384 kWh before requiring replacement. Lithium-ion batteries, in contrast, have a higher lifespan of around 3,000 kWh of throughput, with a maximum depth of discharge of 80% and an efficiency of 90%, leading to a total usable energy output of 2,160 kWh before replacement. However, real-world factors such as operational and maintenance (O&M) costs, ambient temperature, and cycling conditions can further reduce the effective lifespan of batteries (Kebede et al., 2021; X. Zhang et al., 2021). To account for these factors, a conservative lifetime estimate of 5 years for lead-acid batteries and 10 years for lithium-ion batteries is assumed, aligning with scientific literature while ensuring a cautious approach that does not artificially extend battery longevity (Kebede et al., 2021; C. Zhang et al., 2017).

Modelling potential system enhancements using HOMER Pro resulted in scenario 2A, comprising a 2 kW_p solar PV system with 15 kWh of lead-acid battery storage. Scenario 2B, in contrast, requires 4 kW_p solar PV system paired with 5 kWh of lithium-ion battery storage to meet the same energy demand. Both sub-scenarios are modelled with a 1-kW inverter. The complete technical system setup is presented in Figure 29.

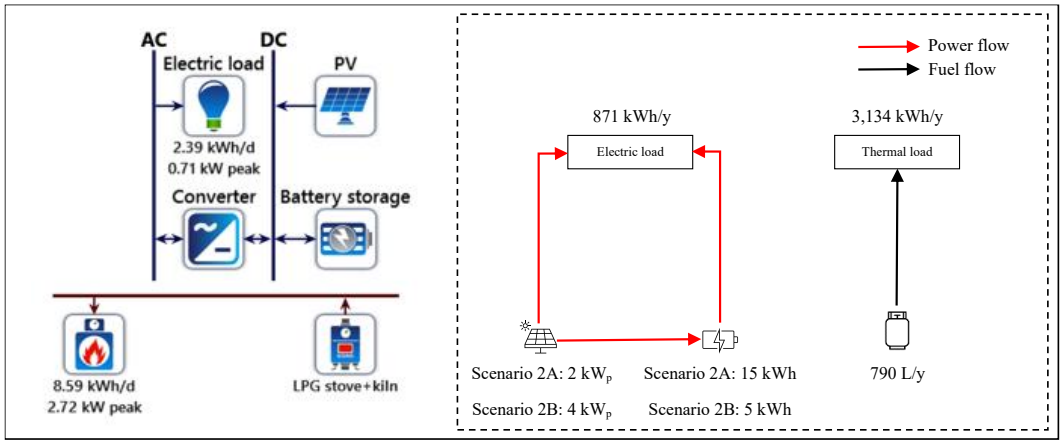

Figure 29. Case study 1: Technical setup of scenario 2

Notes: The left graphic was modelled with HOMER Pro, and the right graphic was modelled by the author. Scenario 2A contains lead-acid battery storage, while scenario 2B contains lithium-ion battery storage.

Abbreviations: kW = kilowatt; kWh/d = kilowatt-hour per day; kWh/y = kilowatt-hour per year; kW_p = kilowatt peak; L/y = litres per year; LPG = liquified petroleum gas; PV = photovoltaic

Since there is no change to the thermal energy demand, it will not be further discussed. The focus remains on the electrical supply, which is now provided entirely by solar PV and battery storage.

In both sub-scenarios, 2A and 2B, a renewable energy fraction of 22% is achieved, reflecting the unchanged ratio between thermal and electrical demand. The solar PV and battery systems fully meet the electrical load, with only a negligible unmet demand of 0.02% in scenario 2A and 0.08% in scenario 2B, ensuring nearly complete electrification of the NGO's operations. Scenario 2A, utilising lead-acid battery storage, results in 64% excess electricity generation, which cannot be stored or utilised and is therefore curtailed. However, the lead-acid battery provides an autonomy of 90 hours, exceeding three days. In contrast, scenario 2B, featuring lithium-ion storage, sees even higher curtailed electricity at 83%, while the battery autonomy is reduced to 40 hours (less than two days). In both cases, approximately 52% of the electricity demand is supplied by the battery, while 48% is directly covered by the solar PV system.

From an economic standpoint, scenarios 2A and 2B exhibit comparable NPC, with scenario 2B incurring a 4% higher NPC but achieving a 24% reduction in operating costs. As expected for scenario 2B with increased solar PV capacity and the investment in lithium-ion batteries, the initial costs incurred are 38% higher than

in scenario 2A. Relative to the base case, NPC increases by 192% in scenario 2A and 204% in scenario 2B, while operating costs rise by 95% and 49%, respectively. In both scenarios, the largest cost components are CAPEX for the solar PV and respective battery systems (32% in 2A and 50% in 2B) and LPG consumption (38% in 2A and 36% in 2B). However, scenario 2A incurs significantly higher replacement costs (18% of NPC) due to the shorter lifespan and lower energy throughput of lead-acid batteries, necessitating more frequent replacements. In contrast, scenario 2B, benefiting from the longer lifespan of lithium-ion storage, allocates only 7% of NPC to replacements. O&M costs for the solar PV and battery systems are also lower in scenario 2B, accounting for 5% of NPC compared to 9% in scenario 2A which is attributed to the smaller battery capacity in scenario 2B.

In terms of environmental impact, scenario 2 only considers scope 1 emissions from LPG combustion, which amounts to 1.23 $tCO_{2\text{-}eq}$/year. This represents a 76% reduction compared to the base case and a 13% reduction relative to scenario 1, highlighting the potential emissions savings achieved through the transition to a system based fully on renewable energy for electricity supply.

Scenario 3: Enhanced electric supply and FAO-FTT kilns for fish smoking

Scenario 3 transitions to more sustainable energy practices by focusing on improving the energy efficiency and environmental sustainability of kilns used in fish smoking processes. While the electric supply components of this scenario, such as the use of solar PV in combination with lead-acid or lithium-ion batteries (scenarios 3A and 3B) and the potential for net metering (scenario 3C), do not introduce new elements beyond those discussed in previous scenarios, the key innovation in this scenario lies in the partial replacement of LPG with a more sustainable, renewable biomass source. Scenario 3 adopts FAO-FTT kilns powered by coconut husks, a locally available biomass byproduct, to enhance the fish-smoking process, while LPG is still used for frying. Developed in 2015 by the FAO in collaboration with the National Training Centre for Fisheries and Aquaculture Technicians (CNFTPA) in Senegal (Ndiaye et al., 2015; Nyemah & Rotawewa, 2021), the FAO-FTT framework aims to improve smoking efficiency, ensure compliance with food safety standards critical for export markets, and reduce the formation of harmful PAH. By utilising cleaner-burning biomass, this technology helps reduce the environmental impact of fish-smoking practices. The choice of FAO-FTT kilns, enhanced with coconut husks, is based on documented successes in similar projects across Africa and Asia, which have demonstrated the feasibility of locally sourcing materials and labour for kiln construction (Mindjimba, 2020;

Ndiaye et al., 2015; Nyemah & Rotawewa, 2021). Additionally, the kiln is adaptable as a multi-food processing device, expanding its utility beyond fish smoking (Ndiaye et al., 2015). The kiln's simplicity and low-cost nature make it suitable for local development and material sourcing, with the overall cost higher than traditional kilns or the Chorkor kiln but still within a reasonable range (Mindjimba, 2020; Nyemah & Rotawewa, 2021). The FAO also recommends several fuels, including coconut husks, corn cobs, and charcoal, which are safer and more sustainable than conventional fuels. Biogas, although a potential alternative to LPG, remains in early research stages and is not included in this study (Ogundana et al., 2022; Olumurewa et al., 2020).

The FAO-FTT kiln consists of four main components: the housing (kiln), smoking racks for placing the fish, fat collection trays (which are an innovation and not present in conventional kilns), and a furnace that holds the fuel (Ndiaye et al., 2015). The fat collected can be further processed into products like soap or sold as oil, adding an income stream. Furthermore, the kiln is equipped with lids to cover the products and reduce exposure to smoke. It is recommended by the FAO that the kiln be housed within a shed to provide a protected environment for processing (Ndiaye et al., 2015; Nyemah & Rotawewa, 2021). Since the NGO already has an existing shed, it is assumed that this structure can be utilised, facilitating implementation without additional infrastructure costs.

Unlike the existing setup, which uses three different kilns for fish processing, the new system would require investment in a single kiln capable of managing the entire drying and smoking process. Given the NGO's current annual fish output of approximately 2.4 tonnes (Gad & Leone, 2025), the kiln capacity was scaled accordingly to avoid underutilisation and ensure that it is appropriately sized for the expected daily production. Typically, FAO kilns are designed for larger capacities, ranging from 0.5 to 3 tonnes/day (Mindjimba, 2020), but scaling down to match the NGO's output is feasible, especially since the design of the kiln is flexible and can be adapted based on specific needs (Nyemah & Rotawewa, 2021). The estimated cost of constructing the kiln, based on FAO's experience with local labour and materials from a project in Micronesia, is approximately 67 USD/kiln. Although the cost is higher than that of traditional Chorkor kilns, which use charcoal or firewood, it is comparable to the cost of LPG-based kilns, primarily due to the associated equipment needed for gas systems (Mindjimba, 2020; Mondo et al., 2021; Nyemah & Rotawewa, 2021; Ogundana et al., 2022). The expected lifespan of the kiln's outer frame is around 15 years, while the interior materials, which are

subject to more wear, will need to be replaced twice over the project's lifetime, with an expected lifespan of 10 years (Mindjimba, 2020).

Regarding the use of coconut husks as fuel, the FAO estimates a cost of 0.10 USD/kg (Ndiaye et al., 2015). While it is possible that the NGO may obtain the husks for free, the cost estimate assumes some expenditure for collection, transportation, and delivery. Given the thermal demand of the kiln, which is approximately 2,685 kWh/year, and the LHV of coconut husks at 10.01 MJ/kg (Amoako & Mensah-Amoah, 2019), it is estimated that nearly 2.7 tonnes of coconut husks would be required annually. Cross-referencing with a general FAO guideline that suggests 1.1 kg of coconut husk is needed for every 1 kg of fish, these estimates align reasonably well (Ndiaye et al., 2015). Consequently, the efficiency of the FAO-FTT kiln can be assumed to be approximately 36%, which is consistent with the expected performance improvements over traditional charcoal or firewood kilns, where efficiency typically hovers around 22% (Ballard-Tremeer & Jawurek, 1996; Ekouedjen et al., 2020; Ndiaye et al., 2015). The complete technical setup, highlighting electrical and thermal demand and distinguishing between sub-scenarios, is presented in Figure 30.

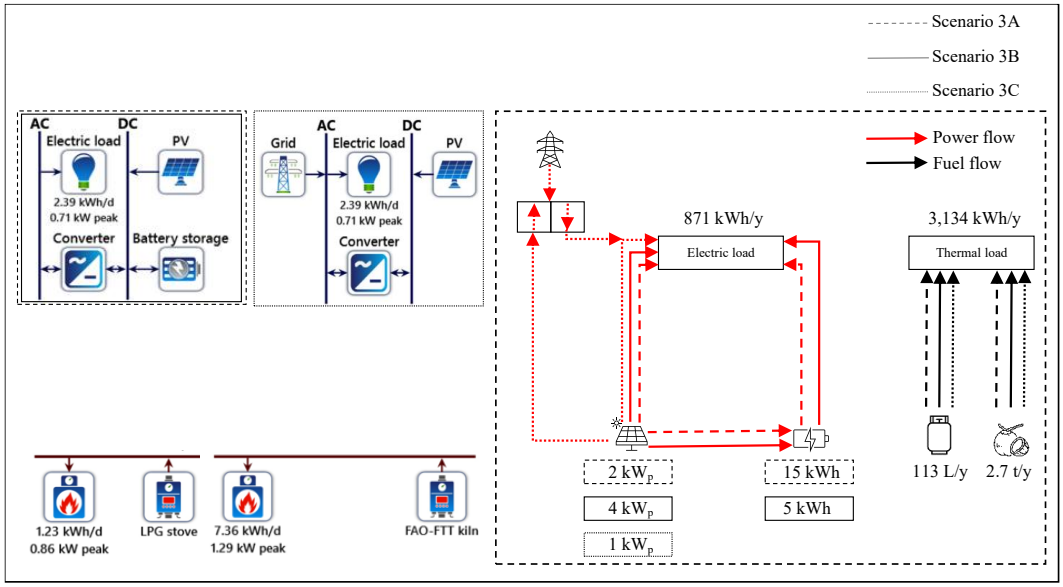

Figure 30. Case study 1: Technical setup of scenario 3

Notes: The left graphic was modelled with HOMER Pro, and the right graphic was modelled by the author. Scenario 3A contains lead-acid battery storage, while scenario 3B contains lithium-ion battery storage. Scenario 3C considers net metering.

Abbreviations: kW = kilowatt; kWh/d = kilowatt-hour per day; kWh/y = kilowatt-hour per year; kW_p = kilowatt peak; L/y = litres per year; LPG = liquified petroleum gas; PV = photovoltaic; t/y = tonne per year

Scenario 3 maintains the same electrical supply configurations as previous scenarios, ensuring continuity in system design. Specifically, scenario 3A corresponds to scenario 2A, integrating a 2 kW_p solar PV system with lead-acid battery storage. Scenario 3B mirrors scenario 2B, incorporating lithium-ion batteries, resulting in a 4 kW_p solar PV system with 5 kWh of storage. Scenario 3C follows the net metering approach of scenario 1, with 551 kWh/year purchased from the grid and 1,057 kWh/year sold as excess. The primary distinction in scenario 3 lies in its focus on thermal energy demand, transitioning the fish-smoking process entirely to FAO-FTT kilns fuelled by coconut husks. This setup requires approximately 2.7 tonnes of coconut husks per year, generating 2,685 kWh/year of thermal energy, with the remaining 449 kWh covered by the LPG stove with a consumption of 113 L/year. Consequently, the thermal energy demand now achieves an 86% renewable fraction, while the renewable fraction of electricity supply varies by sub-scenario: 100% in 3A and 3B, and 37% in 3C, where nearly two-thirds of electricity is sourced from the grid.

From an economic perspective, scenario 3 requires only minor investments, as FAO-FTT kilns and coconut husks represent a low-cost fuel alternative. Across all sub-scenarios, investment costs contribute less than or around 1% of the NPC. The shift from LPG to coconut husks significantly reduces reliance on LPG, which now accounts for only 7% of NPC in scenarios 3A and 3B and 15% in scenario 3C. The cost of coconut husks constitutes 18% of NPC in scenarios 3A and 3B but increases to 40% in scenario 3C, as there are fewer cost-intensive components aside from the additional 1 kW_p solar PV, which contributes 26% of NPC. In scenario 3C, remaining costs primarily stem from grid electricity supply, investment in a bidirectional meter, and minimal contributions from O&M and replacement expenses. Economic outcomes are primarily shaped by the electrical supply configuration: in scenario 3A, solar PV CAPEX account for 23% of NPC, while in scenario 3B, this increases to 48%. Battery CAPEX costs are comparable, at 16% in 3A and 17% in 3B, yet replacement costs differ significantly. Lead-acid battery replacements in scenario 3A contribute 22% of NPC, whereas lithium-ion battery replacements in scenario 3B represent only 9% of NPC. Compared to the base case, scenario 3C has the lowest cost increase of just 8%, making it nearly equivalent in economic terms. Scenarios 3A and 3B result in similar cost increases of 140% and 135%, respectively. Operating costs follow a different trend: scenario 3C achieves

the greatest reduction, with a 23% decrease compared to the base case, followed by 3B at 21%, while scenario 3A sees a 43% increase due to lead-acid battery maintenance. However, the economic advantage in scenario 3C comes at the expense of grid reliance, which, according to the interview data, is a concern due to frequent power outages (Gad & Leone, 2025). In contrast, scenarios 3A and 3B provide fully independent electricity supply systems.

In terms of environmental impact, scenario 3 achieves the lowest GHG emissions among the assessed enhancement scenarios. Only scope 1 emissions from LPG combustion for fish frying are accounted for in scenarios 2A and 2B, amounting to a minimal 0.18 $tCO_{2\text{-}eq}$/year. In scenario 3C, additional scope 2 emissions from grid electricity consumption contribute another 0.2 $tCO_{2\text{-}eq}$/year.

Scenario analysis summary

In evaluating the scenarios for improving the energy efficiency and sustainability of the NGO's fish processing operations, several key themes emerge. First, all scenarios share the fundamental goal of moving away from traditional smoking methods, which pose serious health risks due to harmful emissions and high levels of PAHs. This transition is critical not only for health reasons but also for expanding market access, particularly for export markets with strict food safety standards. Another unifying improvement across the scenarios is the introduction of a pre-smoking greenhouse dryer, designed to improve hygiene, reduce product losses, and enhance operational efficiency. By addressing the inefficiencies of open-air drying, this simple technology offers significant benefits to the fish-smoking process, which aligns with the NGO's focus on quality and product consistency. While more advanced drying technologies were not considered due to their complexity and higher costs, the greenhouse dryer represents a cost-effective solution that enhances both product quality and energy efficiency.

The core differences between the scenarios lie in their approach to energy supply. Scenario 1 introduced solar PV with net metering to reduce electricity costs, while replacing traditional biomass with LPG for thermal energy needs. Scenario 2 built upon this by replacing grid electricity entirely with solar PV and battery storage, thereby moving towards full energy independence. The two sub-scenarios in scenario 2 explored the trade-offs between lead-acid and lithium-ion batteries, offering insights into cost, lifespan, and operational efficiency. Scenario 3 stood out for its focus on improving the environmental sustainability of the thermal energy supply, transitioning from LPG to coconut husks for fish smoking. The introduction

of FAO-FTT kilns powered by this renewable biomass offers a sustainable solution that not only reduces GHG gas emissions but also capitalises on locally available resources. Additionally, this scenario explored various configurations of electrical supply, from solar PV with battery storage to a net metering system, ensuring flexibility in the NGO's approach to energy management. Table 18 summarises the key economic and environmental indicators for each scenario in comparison to the base case.

Table 18. Case study 1: Comparison of initial investment, NPC, annual operating costs and GHG emissions between base case and scenarios 1-3

	Initial investment	**NPC**	**Operating costs**	**GHG emissions**
Unit	USD	USD	USD/year	$tCO_{2\text{-}eq}$/year
Base case	0	5,700	600	5.16
Scenario 1	2,000	9,000	800	1.43
Scenario 2A	5,500	16,600	1,200	1.23
Scenario 2B	8,800	17,300	900	1.23
Scenario 3A	5,600	13,600	900	0.18
Scenario 3B	8,900	13,300	500	0.18
Scenario 3C	2,100	6,100	500	0.37

Notes: All cost figures in USD are rounded to the nearest hundred to enhance readability and facilitate comparison.

Abbreviations: $tCO_{2\text{-}eq}$ = tonne of carbon dioxide equivalent; GHG = greenhouse gas; NPC = net present cost; USD = United States dollar

While the focus of this assessment is on conventional techno-economic and environmental indicators, such as CAPEX, NPC, operational costs, emissions reductions, and energy efficiency, it is important to acknowledge the additional

potential benefits that could further enhance the feasibility and scalability of these interventions. The integration of greenhouse dryers and FTT kilns presents notable advantages beyond cost savings and environmental impact. These technologies accelerate drying and smoking processes, reducing overall processing time and enabling higher daily production volumes with improved resource utilisation (Al-Mashruqi & Al-Ismaili, 2021; Mindjimba, 2020; Mustapha et al., 2014). Additionally, their ease of use reduces the labour-intensive nature of traditional methods, minimising physical strain on workers and improving workflow efficiency. Furthermore, the controlled environments they provide contribute to superior product quality, ensuring uniform moisture levels, consistent smoke penetration, and lower contamination risks. These improvements could enhance marketability and support compliance with food safety standards, potentially facilitating access to higher-value markets.

Ultimately, the choice of which scenario to implement depends on the regulatory framework, the specific goals and priorities of the NGO, and the availability of investment opportunities or grant funding. For example, Scenario 1 offers a straightforward solution with moderate cost increases and a significant reduction in emissions, making it ideal for organisations with limited funding or a cautious approach to innovation. In contrast, scenario 3, particularly its sub-scenarios 3A and 3B, provides the most sustainable option, with the greatest potential for long-term cost savings and the lowest environmental impact, but it requires a higher initial investment. Each scenario presents unique advantages, and the final decision should align with the NGO's long-term vision for sustainability, market expansion, and financial viability.

7.3.1.3 MTF evaluation

This chapter assesses the enhancement scenarios using the World Bank's MTF to evaluate potential improvements in energy efficiency and sustainability for case study 1.

Several key assumptions underpin the MTF evaluation. It is assumed that existing electrical infrastructure remains unchanged, and the enhanced greenhouse dryer fully meets all drying requirements, considered as non-electrical energy, achieving tier 5 standards. Additionally, LPG in scenarios 1-3, with coconut husks only applicable to scenario 3, are assumed to fully satisfy all remaining non-electrical energy needs. Scenario 1 assumes uninterrupted electricity supply through grid-connected solar PV with net metering, fully meeting demand without

outages. Scenario 2 anticipates minimal unmet electrical load, approximately 0.02%-0.08%, reflecting high reliability. Availability assumptions for scenario 3 follow those in scenarios 1 and 2. Reliability assumptions indicate that scenario 1 experiences no outages, while scenario 2 may face minimal weekly outages averaging 2-8 minutes, which are still considered tier 5 performance. Affordability considerations suggest that scenario 1 offers significant savings through net metering, reducing grid costs substantially below standard tariffs. Scenario 2 is assumed to have electric supply costs at or below the grid tariff, also fulfilling tier 5 affordability criteria. Similarly, coconut husks in scenario 3 are notably cheaper than grid electricity tariffs, resulting in tier 5 performance. LPG costs across all scenarios, however, exceed grid tariffs, achieving tier 4 requirements. Convenience assumptions consider a negligible impact of sourcing LPG and coconut husks on productive use, with electrical supply assumed to have no impact on productive use activities as well. Health assumptions classify LPG use as tier 5 across scenarios due to reduced harmful emissions. However, for scenario 3, assigning a tier 2-3 rating to FTT kilns using coconut husks reflects a critical alignment with World Bank MTF definitions (Bhatia & Angelou, 2015) and the qualitative evidence provided by the FAO (Mindjimba, 2020). While FAO data indicate reduced exposure to heat, smoke, and toxic gases compared to traditional smoking methods, the use of raw coconut husks was assumed, not processed or compressed into briquettes. As raw biomass, coconut husks are not classified as clean fuels or "BLEENS" under MTF criteria (Bhatia & Angelou, 2015), and their combustion produces pollutants such as NO and H_2S (Mindjimba, 2020). The absence of quantified emissions data, particularly $PM_{2.5}$ and CO, prevents the justification of a tier 5 classification. However, if future implementation involves densified or carbonised coconut husk briquettes, this could improve combustion efficiency and emissions, potentially raising the tier. For now, tier 2-3 remains a conservative assumption. Regarding the safety attribute, in the base case, the fire accident was assumed to have been caused by the combustion of traditional solid fuels, such as firewood or charcoal, which are known to pose higher fire risks due to open flames, uncontrolled heat, and flammable residues (Barbosa, 2017; Nyanana et al., 2024). This risk is assumed to be significantly reduced when using LPG or more efficient and enclosed systems like FTT kilns, which offer better combustion control, lower exposure to open flames, and improved safety features (Mindjimba, 2020; Nyanana et al., 2024).

Figure 31 illustrates the progression of energy access from the base case to enhancement scenarios 1-3 for the Ghanaian fish-processing NGO. The base case initially performed poorly at tier 1, particularly impacted by inadequate availability

and reliability from the electric grid and poor health outcomes due to reliance on traditional biomass fuels from fish smoking. Significant improvements are observed in all scenarios, with scenarios 1 and 2 reaching an overall tier 4 performance through the integration of solar PV systems and LPG. Scenario 3 achieves an overall tier 3, constrained by the continued use of coconut husks in FAO-FTT kilns, although its electrical supply independently attains a minimum of tier 4. This scenario still represents notable improvement, elevating the overall performance by at least two tiers compared to the base case.

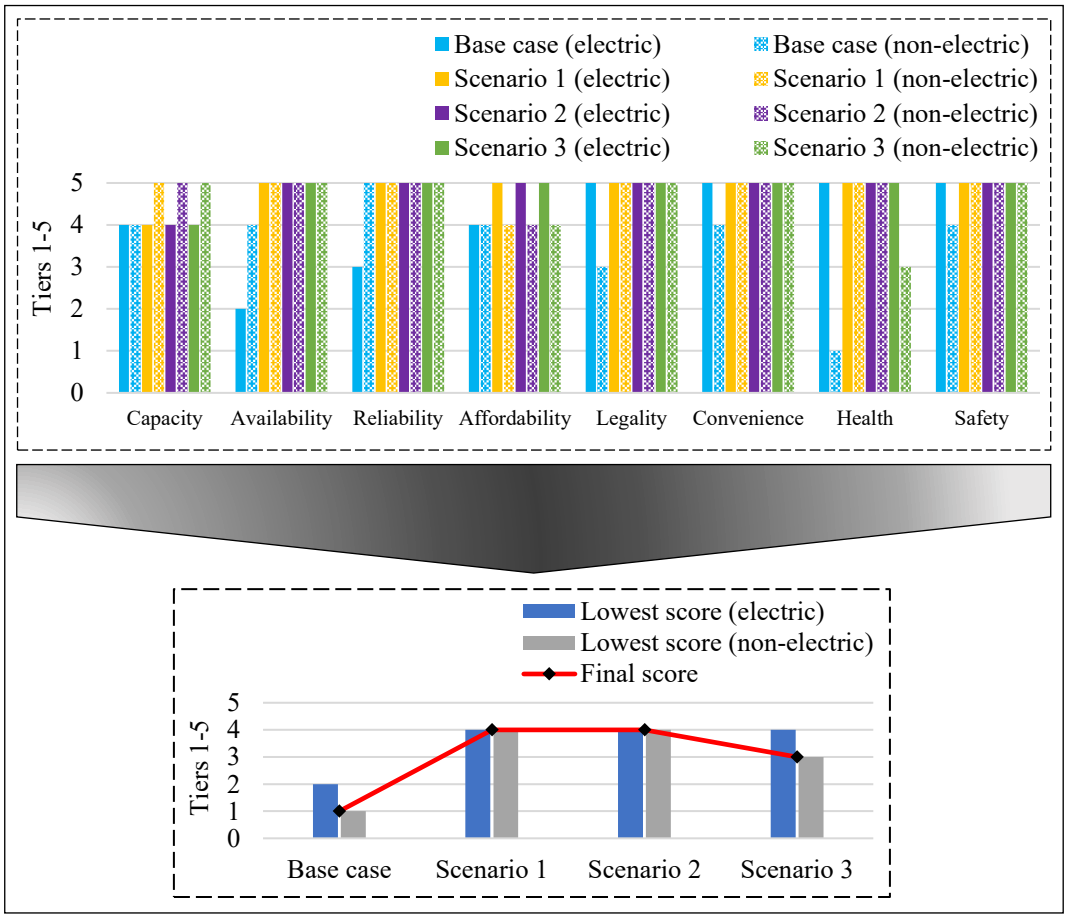

Figure 31. Case study 1: MTF tier performance comparison between base case and scenarios 1-3

These results demonstrate clear benefits from transitioning away from an unreliable grid and traditional fuels toward more sustainable and efficient energy systems. Even scenario 3, which incorporates renewable biomass waste, significantly advances energy access and reduces environmental and health impacts. Thus, adopting integrated renewable energy solutions not only enhances

operational reliability and health outcomes but also meaningfully advances overall energy sustainability.

7.3.2 Case study 2: Tunisia – Crop production and agri-processing

A female entrepreneur in Sidi Bouzid, Tunisia, operates a micro-enterprise cultivating a 12-hectare plot of olive and almond trees. Despite a profit margin of less than 1%, with all earnings directed toward repaying debts from previous investments, the enterprise has significant growth potential. Currently, her production capacity is modest, yielding annually 5 tonnes of olives, with 3 tonnes being processed into 770 litres of olive oil. However, as her trees mature, production is projected to increase tenfold, reaching 50 tonnes of olives and nearly 8,000 litres of olive oil per year. This growth represents a promising economic opportunity but also introduces new operational challenges. Key activities include irrigation and olive oil extraction, which generate organic waste primarily during the olive harvesting and processing periods, occurring three times per year. While waste production is concentrated in these seasonal peaks, it averages approximately 12 kg/day over the course of the year, consisting of 4.5 kg of olive press cake and 7.5 litres of olive wastewater (Keskes et al., 2022).

As a sole proprietor, the entrepreneur faces several challenges. Business obstacles include the lack of machinery for crop automation, the adverse effects of environmental degradation on soil and tree health, and limited irrigation capacity, as her solar PV system cannot fully meet the irrigation needs. Gender-related challenges also persist in this traditionally male-dominated sector, including gender-biased attitudes toward women in agriculture and cultural restrictions, such as being unable to work at night.

Limited access to financing remains the primary hurdle to increasing the renewable energy share in her production process, but she is motivated by economic savings, environmental sustainability, and her commitment to eco-friendly practices to expand on the existing renewable energy technology for her business. Her decision on new investments will ultimately depend on finding a balance between affordability and the long-term sustainability of her business.

Applying the World Bank's MTF, the enterprise achieves an overall energy access score of 2. The score reflects significant limitations in solar PV availability, necessitating the addition of the diesel generator. However, the use of fossil fuels negatively impacts health-related performance, despite the generator being housed

in a separate, covered area outside the home. High transportation and service fees, along with time-consuming travel to an external processing facility, result in poor performance in terms of convenience and affordability for electric energy use.

This contextual overview lays the groundwork for a more detailed exploration of the enterprise's existing energy profile. The subsequent section presents the base case analysis, examining the current energy access status, the technical and economic characteristics of the operational setup, and its associated environmental impacts. This serves as a critical reference point for evaluating the performance and benefits of the proposed energy enhancement scenarios.

7.3.2.1 Base case

The entrepreneur's energy system relies on grid electricity for olive oil processing at an external facility located 80 km from her farmland. For pumping and irrigation, she uses a solar PV-powered pump combined with a grid-powered electric motor-driven pump. Following a face-to-face interview in April 2023, the entrepreneur received a diesel generator in 2024 to address energy shortfalls. As of December 2024, the agricultural irrigation system is powered by a solar PV hybrid system, supplemented by a diesel generator. The hybrid system was provided through a scholarship programme that substantially reduced if not entirely covered, capital and installation costs. In 2019, the entrepreneur received a subsidy from the Tunisian National Agency for Energy Management (ANME), covering 40% of the 14.49 kW_p solar PV system's CAPEX, excluding taxes. This subsidy left the entrepreneur with an investment cost of approximately 12,200 USD. In 2024, the entrepreneur became a beneficiary of the ProAgro programme, which supports sustainable agri-food micro-enterprises in disadvantaged regions, including Sidi Bouzid. Through this initiative, the CAPEX for a new diesel generator was fully funded.

The enterprise's monthly energy costs, exclusive of the remaining solar PV loan amount to around 743 USD/month. The energy expenditure is primarily attributed to diesel fuel, which costs approximately 462 USD/month. Routine oil changes, performed seven times annually, add 37 USD/month, while fuel transportation and logistics incur another 37 USD/month. At a grid tariff of around 14.33 USD¢/kWh, inclusive of energy charges and taxes (Société Tunisienne de l'Electricité et du Gaz (STEG), 2022), on-site grid electricity costs approximately 170 USD/month. Furthermore, olive processing at an external facility, including transportation and service fees, adds another 37 USD/month.

The water pumping system for the crop operates on a solar PV hybrid setup, complemented by a diesel generator and a grid-powered motor-driven irrigation pump, designed to meet the varying water demands of the crop land throughout the year. The infrastructure integrates multiple critical components, ensuring efficient water management, while for olive oil processing, the harvested produce is transported to a facility located 80 km away, as on-site processing is not available. The key productive use applications are summarised in Table 19.

Table 19. Case study 2: Summary of productive use applications

Process	Temperature	Energy carrier	Appliance		Power rating or consumption	
	°C	Type	Count	Type	Value	Unit
Pumping	-	Solar PV-based electricity; Diesel-based electricity	1	Water pump	7.5	kW
Irrigation	-	Grid electricity	1	Irrigation pump	4	kW
Oil extraction	-	Grid electricity	1	Oil press	30	kW

Notes: The solar PV system has an installed capacity of 14.49 kW_p, while the generator has a capacity of 33 kW.

Abbreviations: °C = degree Celsius; kW = kilowatt; PV = photovoltaic

A clearer understanding of the on-site infrastructure and equipment specifications allows for an estimation of the daily energy demand and a more precise characterisation of the enterprise's consumption profile. A 7.5-kW rated water pump extracts water from a borehole located around 70 meters underground, powered by a 14.49 kW_p solar PV hybrid system and supported by a 33-kW diesel generator. The mechanical power required by the pump depends on the necessary flow rate and head (the height to which the water is lifted). With a flow rate of 18 m^3/h and a head of 73.5 meters (m), the calculated power requirement is 3.6 kW.

Although the pump has a rated capacity of 7.5 kW, it typically operates at 60% of this capacity, corresponding to 4.5 kW. Given the pump's 80% efficiency, the input power required to achieve the 3.6 kW output is 4.5 kW, accounting for inherent energy losses in the system.

The irrigation schedule varies throughout the year, reflecting seasonal water needs. On an annual basis, the calculated average daily water consumption averaged over the year is approximately 123 m^3/day (compared to 126 m^3/day as per the data sheet from the entrepreneur). However, demand fluctuates significantly. From February to October, irrigation is required daily, with actual water usage averaging 150 m^3/day. This period coincides with peak summer months, where high evapotranspiration increases water consumption and surface evaporation from the storage basins. Conversely, from November to January, irrigation needs decrease due to lower temperatures, occasional rainfall, and reduced evapotranspiration. During this period, the basins are filled only three times per week, requiring just 100 m^3 each time, leading to a significant reduction in water and energy consumption.

The irrigation system relies on a 14.49 kW_p solar PV system, which operates during daylight hours and fills the 100 m^3 basin in approximately 5 to 7 hours, depending on seasonal variations. Based on the total seasonal water demand and the 18 m^3/h flow rate, the estimated borehole pump energy consumption is around 32 kWh/day on average throughout the year. To meet the remaining 50 m^3 shortfall from February to October, a 33-kW diesel generator operates exclusively during nighttime hours, running from 21:00 to midnight and again from 4:00 to 6:00. The generator primarily powers the borehole pump, ensuring adequate water extraction while avoiding overheating risks. Additionally, it occasionally supports the irrigation pump during nighttime when grid reliability is an issue. From November to January, as overall irrigation demand decreases, the diesel generator operates on a reduced schedule, only three days per week, but still follows the same nighttime operation pattern. Although only 100 m^3 of water is required for irrigation on these days, the additional 50 m^3 is pumped and sold as an extra income stream.

The extracted water is first stored in a 100 m^3 ground-level capture basin and a 16 m^3 elevated basin before being distributed to the fields. The irrigation system uses a 4-kW electric motor-driven pump, powered by the electric grid, with occasional use of the diesel generator when the grid is unreliable. With a flow rate of 16 m^3/h, this irrigation pump has the same annual average electrical energy

consumption as the borehole pump amounting to around 31 kWh/day, resulting in around 11,235 kWh/year.

An earlier attempt to integrate the irrigation pump with the solar PV system during sunlight hours proved impractical, as simultaneous operation of both water extraction and distribution conflicted with fieldwork schedules and manual irrigation supervision. Additionally, the manual nature of irrigation requires on-site supervision, and the entrepreneur is not always available to manage these tasks. To ensure operational flexibility, she sometimes delegates irrigation work to family members. Maintaining the current configuration, where the solar PV system and diesel generator power the borehole pump while the grid powers the irrigation pump primarily, remains the most straightforward and reliable setup for her and her family. The complete technical setup is illustrated in Figure 32.

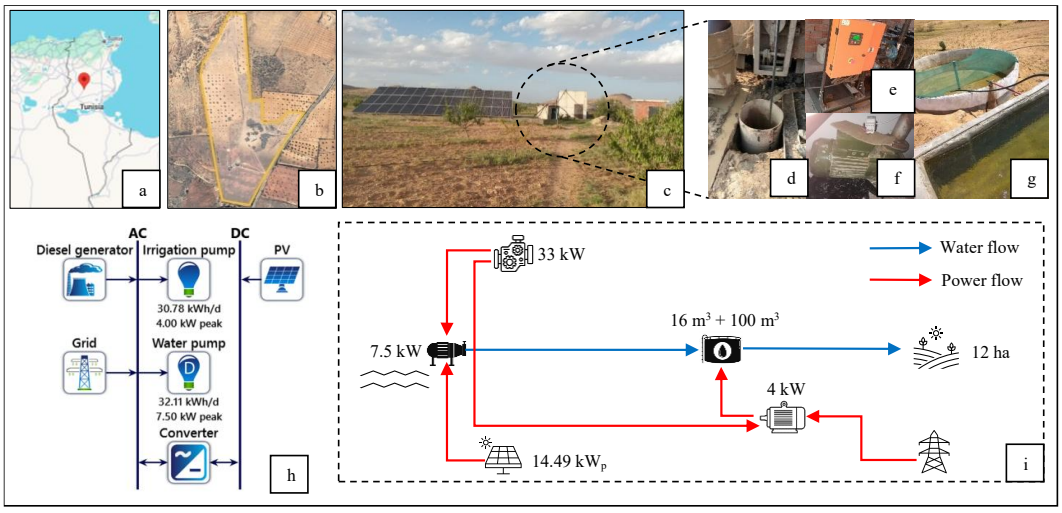

Figure 32. Case study 2: Technical setup of the base case

Notes: a) Geographic location, source: google.maps; b) Land plot, source: entrepreneur (used with permission and author holds rights to use and publish); (c-g) On-site pictures of technical equipment, source: entrepreneur (used with permission and author holds rights to use and publish); c) Solar PV panels and shed protecting; d) Surface structure above the borehole housing the 73.5 m deep water pump; e) Diesel generator; f) Electric motor-driven pump for irrigation; g) 16m^3 and 100 m^3 water basins; h) Technical setup designed with HOMER Pro; i) Technical setup designed by the author.

Abbreviations: ha = hectare; kW = kilowatt; kWh/d = kilowatt-hour per day; kW_p = kilowatt peak; m^3 = cubic meter; PV = photovoltaic

The current economics of the Tunisian case study reveal significant operational expenditures across various components of the solar PV-diesel hybrid irrigation system and olive oil processing activities.

As per the setup, the diesel generator operates daily from February to October (273 days) and less frequently from November to January (42 days), totalling 315 days per year. With an average fuel consumption of 20 litres per day at a cost of approximately 15 USD/day, the annual diesel expenditure amounts to 4,787 USD. Additionally, fuel transportation and logistics contribute 444 USD/year, while routine oil changes, required seven times annually, add another 426 USD/year. The generator replacement costs are estimated at 600 USD/kW, resulting in a total of 19,800 USD for each replacement. Given the generator's estimated operational lifespan of 20,000 hours and its relatively limited annual operating hours, the generator is expected to require replacement twice over the 25-year project lifetime, anticipated in years 11 and 22.

Since the entrepreneur primarily manages operations alone, with occasional assistance from family members, no additional labour costs are considered in the base case. Standard O&M costs for the solar PV system are set at 10 USD/kW/year (ESMAP, 2022). For the diesel generator, O&M costs, including fuel transportation, general maintenance, and regular oil changes, amount to 869 USD/year, equivalent to 0.019 USD/kW per operating hour.

The electric motor-driven irrigation pump is primarily powered by the grid, with occasional diesel supply due to grid outages. However, for calculation purposes, only grid consumption is considered, resulting in an annual energy cost of 1,610 USD/year. Olive oil processing adds further costs, including 365 USD annually for transporting olives and 76 USD/year for processing services, totalling 441 USD/year.

The financial analysis was conducted over a 25-year project lifetime using a discount rate of 10.7%, which reflects the cost of capital (CoC) for Tunisia as reported by IRENA (Taylor et al., 2023). The NPC amounts to 87,927 USD, while operating costs account for 8,799 USD/year. Table 20 presents the economics of the base case in more detail. The diesel generator-related costs, including fuel, O&M, and replacement expenses, account for 65% of the total system costs, representing a substantial portion of the financial burden. Additional costs arise from the solar PV system (16% of NPC). Grid electricity costs, which contribute 16% to the overall expenses, also play a significant role in the economic dynamics

faced by the entrepreneur. The system retains a salvage value of slightly above 1%, reducing the overall NPC modestly.

Table 20. Case study 2: Net present cost and operating costs of the base case

Component	NPC (USD)	Operating costs (USD/year)	Share of NPC (%)
Diesel generator			
O&M (maintenance, transport)	7,484	869	9%
Fuel consumption	41,217	4,787	47%
Replacement	8,588	997	10%
Solar PV system			
CAPEX PV	12,168	1,413	14%
O&M PV	1,248	145	1%
Replacement converter	784	91	<1%
Electric motor for irrigation			
Grid electricity	13,861	1,610	16%
Olive oil extraction			
Transport and service fees for oil extraction	3,795	441	4%
Total salvage value	-1,215	-221	-1%

Total	**87,927**	**8,799**	**100%**

Notes: A nominal discount rate of 10.7% is applied, and the project lifetime is set for 25 years. Due to rounding, the sum of individual items may not exactly match the total.

Abbreviations: % = percent; CAPEX = capital expenditure; NPC = net present cost; O&M = operation and maintenance; PV = photovoltaic; USD = United States dollar

To place the productive use patterns of case study 2 in a broader sustainability context, their environmental implications were assessed by calculating both direct and indirect GHG emissions across scopes 1-3, following the GHG Protocol and PCAF guidelines (PCAF, 2020, 2022; UNFCC Secretariat, 2022).

Scope 1 emissions, from diesel combustion in the generator, amount to 15.89 $tCO_{2\text{-}eq}$/year. Scope 2 emissions, resulting from electricity use on and off-site, total 4.58 $tCO_{2\text{-}eq}$/year. Scope 3 emissions, primarily from transportation for fuel procurement and olive oil processing, contribute 0.26 $tCO_{2\text{-}eq}$/year. In total, the base case emissions across all scopes over a 25-year project lifetime result in 518.25 $tCO_{2\text{-}eq}$. When considering the enterprise's production output, these emissions are equivalent to 3.59 $tCO_{2\text{-}eq}$/tonne of goods produced.

Building on the challenges outlined earlier, ranging from high energy costs to insufficient supply, the next section identifies optimisation strategies that not only reduce environmental impact but also advance more affordable, reliable, and sustainable energy access for the enterprise.

7.3.2.2 Scenario analysis

A variety of improvement approaches can be implemented to address the weaknesses identified through the MTF analysis, thereby enhancing the operational efficiency and overall energy access of the enterprise. On the supply side, options could include integrating alternative renewable energy solutions, implementing energy storage systems to store excess renewable energy for peak demand periods, or enabling grid interaction to sell surplus electricity. Additionally, automating processes can significantly improve safety and efficiency, reducing the reliance on manual labour for system operation.

On the demand side, employing more efficient electric equipment and conducting energy efficiency audits can help identify inefficiencies and optimise energy use. Training staff on best practices for energy management and

implementing demand response programmes are also effective strategies to further reduce consumption.

Another essential upgrade involves installing a protective fence to safeguard the crop land from wild animals, with an estimated investment of around 36,500 USD, according to the entrepreneur's estimation. This measure, while not directly related to supply or demand management, plays a crucial role in protecting investments made and ensuring the sustainability of crop management.

However, the primary focus of this techno-economic analysis will be on exploring energy solutions that can enhance the system's overall sustainability and cost-effectiveness. For this analysis, the focus lies on measures that can be effectively modelled using HOMER Pro. This involves evaluating the economic feasibility of upgrading technological components, improving system efficiency, and integrating alternative energy solutions, such as enhanced energy conversion equipment, advanced machinery, or fully renewable systems with energy storage. By concentrating on these specific strategies, the analysis aims to identify the most viable options for improving the enterprise's overall energy access performance.

Building on the detailed description of the base case provided earlier, this section summarises the three optimisation scenarios, all modelled over a 25-year period with a 10.7% nominal discount rate (Taylor et al., 2023). While the base case represents the current system, which relies on a combination of solar PV, diesel, and grid electricity, the scenarios eliminate diesel dependence, improve system efficiency, and integrate renewable energy solutions.

Scenario 1: Eliminating diesel reliance and improved system efficiency

One of the key technical enhancements for the current system in the Tunisian case study involves eliminating the diesel generator. This optimisation proposes enabling the existing solar PV system, alongside the electrical grid, to power the electric motor-driven irrigation pump, which distributes water from the basin to the fields. Meanwhile, the grid, in combination with the solar PV system, would power the borehole pump. Currently, this configuration is not available as the borehole pump requires a 380 V supply, while the grid provides electricity at 220 V, which is sufficient for the electric irrigation motor. To allow the solar PV system to power the irrigation motor, a step-down transformer is required to convert the 380 V to 220 V to supply the 4-kW irrigation motor.

With investment in the necessary infrastructure and equipment, this scenario was assessed using HOMER Pro to explore potential improvements. Based on cost estimates from the Tunisian Electricity and Gas Company (STEG, 2021) and the entrepreneur, an estimated investment of approximately 15,500 USD is required, primarily for the connection to the 380 V grid line. The entrepreneur is located 700 meters away from the line, which places her at the higher end of the investment required for such a connection.

HOMER Pro was instrumental in determining the most cost-effective operational strategy. The software optimises the system to prioritise filling the water basin at the lowest possible cost, ideally using solar PV. When solar energy is unavailable, the electrical grid is used, ensuring sufficient water is always available for irrigation. The grid and solar PV system were configured to jointly power both the submersible water pump and the irrigation pump, eliminating the need for the 33-kW diesel generator. However, this setup assumes grid reliability, and during grid outages, when the grid is the only option, there may be a gap in supply. In practice, the entrepreneur could use the diesel generator as a backup in such cases, but this contingency is not considered in the techno-economic model of scenario 1. As illustrated in Figure 33, the system architecture is based on the current configuration but optimises the use of existing technologies while eliminating the need for the 33-kW diesel generator.

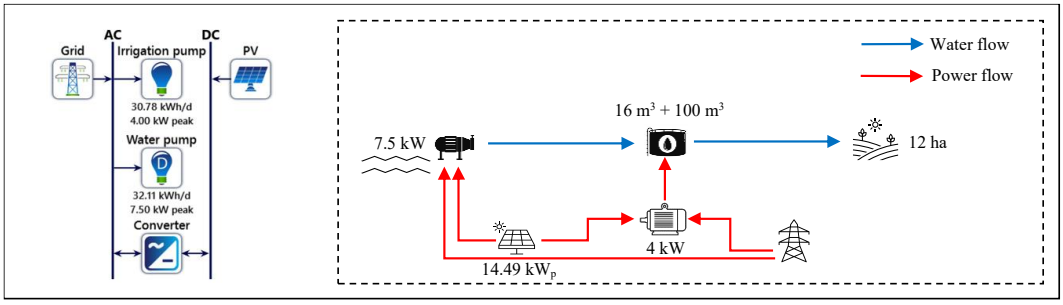

Figure 33. Case study 2: Technical setup of scenario 1

Notes: The left graphic was modelled with HOMER Pro, and the right graphic was modelled by the author.

Abbreviations: ha = hectare; kW = kilowatt; kWh/d = kilowatt-hour per day; kW_p = kilowatt peak; m^3 = cubic meter; PV = photovoltaic

In scenario 1, the energy supply in the system is distributed between the solar PV system and the electrical grid, with a renewable fraction of nearly 70%, meaning that 70% of the total demand is met by the existing solar PV system.

Compared to the base case, grid purchases have been reduced to 7,096 kWh/year, representing a 37% reduction. The solar PV system generates a surplus of 19% or 5,587 kWh/year, which is curtailed. However, 15,821 kWh is effectively supplied to the borehole and irrigation pumps after accounting for existing losses in the inverter system. This configuration marks a significant improvement in the system's efficiency, with a notable reduction in diesel (complete elimination) and grid electricity dependence, making better use of the renewable energy resources available.

From an economic perspective, scenario 1 assumes a setup broadly comparable to the base case, with the main capital investment directed toward establishing a 380 V grid connection, installing a step-down transformer, and acquiring additional equipment to enable the energy transition. The scenario further assumes that the entrepreneur continues to operate the business independently, without hiring additional staff. With operations remaining largely consistent, except for improved utilisation of existing technologies supported by targeted infrastructure upgrades, scenario 1 achieves a notable 54% reduction in NPC and a 62% decrease in operating costs relative to the base case.

From an environmental standpoint, and compared to the base case, scenario 1 offers a significant reduction in GHG emissions, with approximately 86% of emissions potentially being avoided. In quantitative terms, this translates to savings of 443.5 $tCO_{2\text{-}eq}$ over the project's 25-year lifetime. The primary source of these reductions comes from the elimination of diesel fuel use. Additionally, reduced electricity use contributes 1.68 $tCO_{2\text{-}eq}$ in annual savings. Minor reductions are also observed in transportation-related emissions, only required to access the oil extraction facility. The GHG emissions translate to 0.52 $tCO_{2\text{-}eq}$/tonne produced goods, assuming a constant production output compared to the base case.

Scenario 2: Enhancing irrigation efficiency by upgrading pump capacity for higher flow rates

The second scenario assesses future demand as olive and almond trees grow and require increased irrigation. According to the entrepreneur, the required water flow rate will increase from 16 m^3/h to 25 m^3/h, while maintaining all other parameters as compared to scenario 1, such as the size of the water basins, operating

hours, as well as the technical configuration (i.e., the grid and solar PV system jointly supply power to both the borehole and irrigation pumps). Under these conditions, the total water demand increases to 200 m^3/day, including additional water that is pumped for sale but not used for irrigation. The irrigation demand alone accounts for 192 m^3/day. To achieve the increased capacity, the existing motor is replaced with a 5.5 kW motor, capable of pumping 25 m^3/h. This upgrade results in an estimated energy consumption of 43 kWh/day for the borehole pump and approximately 42 kWh/day for the irrigation pump.

The cost estimation for a 5.5 kW electric motor-driven irrigation pump with a 25 m^3/h capacity is approximately 1,200 USD, as per the entrepreneur's estimates. The costs associated with connecting to the 380 V grid line, along with any additional control equipment, are required as per scenario 1. However, no step-down transformer is necessary in this case, as the 5.5 kW irrigation motor operates at 380 V and can be directly powered by the grid and solar PV system. As a result, the total initial investment cost remains similar to scenario 1, amounting to approximately 15,800 USD. Additionally, to accommodate the increasing operational demand, the entrepreneur is considering hiring an employee at a cost of 15 USD per working day.

While the concept of net metering[9] was assessed as a potential scenario, it was not implemented due to financial infeasibility. Under Tunisian law, independent power producers generating electricity from renewable sources for self-consumption may sell up to 30% of their annual production to the national utility, the Tunisian Electricity and Gas Company (STEG) (Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) et al., 2019). Contracts are valid for 20 years and are automatically renewed unless terminated by either party. This case assumes medium voltage (MV) to medium voltage (MV) power lines, with tariffs provided exclusive of VAT (STEG, 2023). For projects approved after December 2023, the purchase price is 0.080 Tunisian Dinar per kWh (DT/kWh), reduced by transportation fees of 0.039 DT/kWh and balancing fees of 0.043 DT/kWh, which results in a final net tariff of -0.002 DT¢/kWh. Given the negative net purchase price, the scheme was deemed unprofitable. While it could offer benefits under different conditions, such as high voltage (HV) to high voltage (HV) power lines, it was ultimately considered unsuitable for this case. However, adjustments to the

[9] Original term in French: Prix de transport, de report et d'achat de l'excédent de l'énergie électrique produite pour l'autoconsommation en haute et moyenne tension (STEG, 2023). English translation: Transport, balancing, and purchase price for surplus electricity generated for self-consumption at high and medium voltage.

regulatory framework and the inclusion of small IPPs in policy support schemes could enhance financial viability, creating more favourable conditions for decentralised renewable energy generation. The final technical setup of scenario 2 is presented in Figure 34.

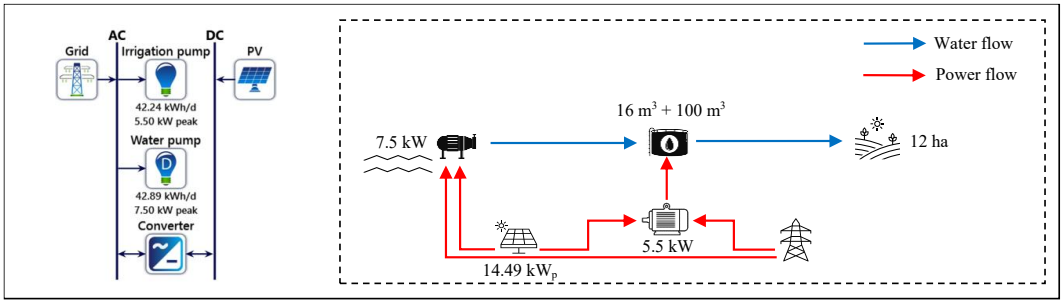

Figure 34. Case study 2: Technical setup of scenario 2

Notes: The left graphic was modelled with HOMER Pro, and the right graphic was modelled by the author.

Abbreviations: ha = hectare; kW = kilowatt; kWh/d = kilowatt-hour per day; kW_p = kilowatt peak; m^3 = cubic meter; PV = photovoltaic

In scenario 2, the solar PV system supplies approximately 55% of the total energy consumption, with the remaining 45% sourced from the electrical grid, amounting to 13,993 kWh/year. On the demand side, energy consumption is almost evenly distributed between the two primary loads. This configuration results in a minimal excess energy generation of only 12%, corresponding to 4,308 kWh/year from the solar PV system that is curtailed. Despite the advantages, the system introduces a greater reliance on the electrical grid, which poses risks in the event of power outages, particularly when solar energy is insufficient to meet demand. As outlined in scenario 1, the diesel generator remains available as a contingency option for such cases, though it is not included in the model design.

This setup, designed to meet future water and energy demands, presents an intriguing cost-benefit analysis. The NPC increases by only 3%, despite the substantial increase in water and energy capacity. The primary cost driver is labour, with hiring an additional employee accounting for 45% of the NPC, making it the most significant expense. However, operating costs decrease by 18% due to the complete elimination of diesel fuel reliance. The initial investment accounts for 31% of the total NPC, which is considered moderate and aligns with long-term sustainability goals by reducing dependency on fossil fuels while increasing irrigation operations.

The environmental impact in scenario 2 is slightly less favourable than in scenario 1 due to increased reliance on the electrical grid. This results in a rise in scope 2 emissions, while scope 3 emissions also increase due to the assumption that a tenfold increase in production would proportionally increase transportation requirements for processing olives at the external facility. However, compared to the base case, scenario 2 demonstrates a substantial reduction in overall emissions, primarily driven by the elimination of the diesel generator, which was the dominant source of GHG emissions. Approximately 69% of total GHG emissions, equivalent to 355 $tCO_{2\text{-}eq}$ over the project's lifetime, could be avoided in scenario 2. Emissions from transportation to the processing facility remain relatively low at 0.84 $tCO_{2\text{-}eq}$/year. Assuming a tenfold increase in production, GHG emissions per tonne of produced goods are significantly reduced to 0.1 $tCO_{2\text{-}eq}$/tonne, underscoring the environmental benefits of transitioning away from diesel dependence.

Scenario 3: Energy autonomy by expanding solar capacity, introducing battery storage, and on-site olive oil extraction

Building on previous scenarios, scenario 3, like scenario 2, considers future water demand while also focusing on achieving long-term sustainability and autonomy for the entrepreneur by eliminating reliance on the grid. This scenario assumes 100% self-consumption, requiring investment in additional solar PV capacity and battery storage to ensure energy security and continuous operation. By addressing both the increased water needs and energy independence, scenario 3 presents a comprehensive approach to enhancing long-term resource management.

Under Tunisian law, any local authority, public or private institution connected to the national electrical grid at medium or high voltage is allowed to generate electricity from renewable energy sources for self-consumption (GIZ et al., 2019). These self-consumption projects enable users to utilise the electricity they produce immediately, reducing their energy bills or potentially eliminating the need for grid reliance.

The assumed CAPEX for the solar PV system is based on the cost of an existing system installed in 2019 by the entrepreneur, with costs scaled linearly according to system size. The 2019 PV system and inverter had a total cost of 1,144 USD/kW_p, which includes hardware, installation, soft costs, and VAT. These figures were verified through documentation provided by the entrepreneur but have not been made public for privacy reasons. This cost estimate is preferred over ESMAP's mini-grid data, as the latter is less representative of this case. For example, ESMAP

estimates a medium cost of 441 USD/kW_p for PV panels and inverters, with 631 USD/kW_p as an average regional value from African and Asian countries (ESMAP, 2022). However, these figures exclude additional costs required for implementation and installation. For further comparison, a 2020 USAID study estimated that the cost of a solar PV system in Tunisia, including 19% VAT could come at a cost of around 832 USD/kW_p, encompassing installation and soft costs, while the inverter is not explicitly listed in the cost breakdown (USAID & Ministry of Local Affairs and Environment (MALE), 2020). For this assessment, the cost of 1,144 USD/kW_p is used, as it closely reflects the actual costs incurred by the entrepreneur and represents a realistic baseline. However, the costs of lead-acid and lithium-ion batteries, set at 153 USD/kWh and 455 USD/kWh respectively, are based on ESMAP's average estimates for the Africa/Asia region, reflecting their relevance to storage cost assumptions (ESMAP, 2022).

To eliminate the need for transporting olives to a distant processing facility, scenario 3 integrates a commercial olive oil press with a processing capacity of 200 kg/h and a power requirement of 12 kW. This capacity was carefully selected to align with production needs while maintaining a cost-effective and energy-efficient setup. Although higher-capacity presses (500-1,000 kg/h) would reduce processing time, they were not considered due to higher capital costs, increased energy demand, and an operational scale exceeding the entrepreneur's current production levels and financial feasibility. To model this scenario in HOMER Pro, future processing capacities were assumed to increase tenfold, reaching 30 tonnes of olives being processed annually. At the selected rate (12 kW, 200 kg/h), the olive oil press would consume approximately 1,800 kWh/year, corresponding to an average of 4.93 kWh/day with seasonal variability during harvest periods. The system must also handle a peak load of 12 kW. The total investment for the olive oil press amounts to approximately 55,300 USD, including a base price of 39,890 EUR, 19% VAT, and 890 EUR shipping to Tunisia[10] (Ölwerk, 2024), and 10% contingency.

Two sub-scenarios were modelled, differing only in battery storage technology. Scenario 3A assumes lead-acid batteries, while scenario 3B considers lithium-ion batteries. Battery longevity is typically defined in terms of energy throughput. Lead-acid batteries have an estimated lifespan of 800 kWh of throughput, with a maximum depth of discharge (DoD) of 60% and an efficiency of 80%, resulting in 384 kWh of usable energy before replacement. In contrast, lithium-ion batteries

[10] Costs in EUR are converted to USD at a rate of 1.04 USD/EUR.

offer a longer lifespan of approximately 3,000 kWh of throughput, with an 80% DoD and 90% efficiency, yielding 2,160 kWh of usable energy. However, real-world factors such as operational and maintenance costs, ambient temperature, and cycling conditions can reduce effective battery lifespan (Kebede et al., 2021; X. Zhang et al., 2021). To account for these uncertainties, a conservative lifetime estimate of 5 years for lead-acid and 10 years for lithium-ion batteries is adopted, aligning with the literature while ensuring a realistic assumption (Kebede et al., 2021; C. Zhang et al., 2017).

HOMER Pro results indicate that achieving a 100% renewable energy system for self-consumption requires an additional 55 kW_p of solar PV for both sub-scenarios, but with 220 kWh of lead-acid storage in scenario 3A, and 155 kWh of lithium-ion storage in scenario 3B. Although HOMER Pro allowed for the addition of a converter, the model identified increasing PV capacity without an additional converter as the most economically optimal solution in both sub-scenarios. As a result, a significant amount of excess electricity is generated and curtailed. This curtailment is driven by the current regulatory framework, which does not provide incentives for small IPPs to feed surplus electricity into the national grid. While the diesel generator remains available, it is not utilised in scenario 3. The full technological setup is illustrated in Figure 35.

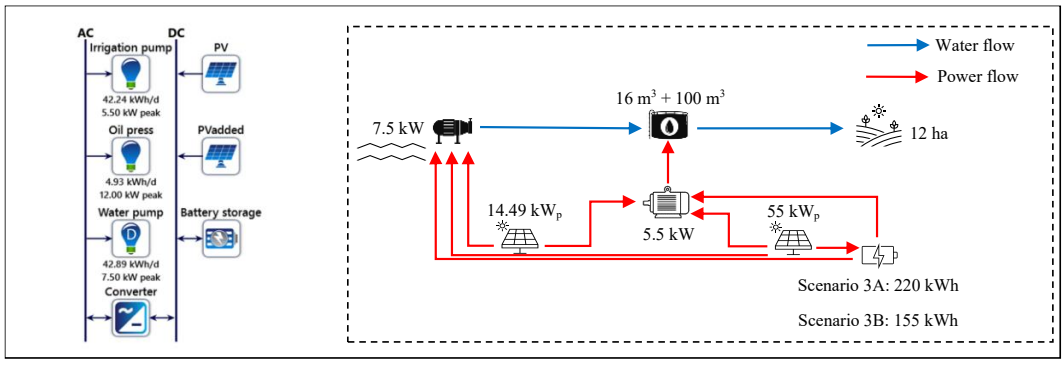

Figure 35. Case study 2: Technical setup of scenario 3

Notes: The left graphic was modelled with HOMER Pro, and the right graphic was modelled by the author. Scenario 3A contains lead-acid battery storage, while scenario 3B contains lithium-ion battery storage.

Abbreviations: ha = hectare; kW = kilowatt; kWh = kilowatt-hour; kWh/d = kilowatt-hour per day; kW_p = kilowatt peak; m^3 = cubic meter; PV = photovoltaic

The 100% renewable energy system with battery storage successfully meets the total energy demand, with only 0.1% of the load unmet, which is negligible and does not indicate significant capacity shortages. The system supplies a total annual demand of 32,806 kWh/year, encompassing the borehole pump, irrigation pump, and olive oil press. However, a considerable amount of electricity is generated in excess, accounting for 67% of total solar PV production, which is effectively curtailed due to the absence of mechanisms for selling surplus energy to the grid.

Both batteries have an estimated autonomy of 33-35 hours, ensuring a stable energy supply during periods of low solar generation. This estimation considers key parameters, including battery count, nominal voltage, ampere-hour (Ah) capacity, a minimum state of charge, and the system's average daily primary load (kWh/day).

Over a 25-year period, assuming a 10.7% discount rate, scenario 3 results in a significantly higher NPC, increasing by 229% and 250% in scenarios 3A and 3B respectively, compared to the base case. While scenario 3B incurs a 7% higher NPC compared to 3A, scenario 3B, featuring lithium-ion battery storage, incurs lower operating costs, rising by 21% compared to 44% in scenario 3A. However, since scenario 3, like scenario 2, is designed to accommodate future demand growth, direct comparisons with the base case should be interpreted with caution.

As expected, in scenario 3A, the initial investment accounts for 62% of the total NPC, while in Scenario 3B, it represents 70% due to the relatively higher costs associated with lithium-ion battery storage technology. Battery replacement costs contribute 15% to NPC in scenario 3A (lead-acid) and 11% in scenario 3B (lithium-ion). Additional costs arise from hiring personnel and the O&M of the solar PV system and battery storage. Scenario 3B demonstrates relatively better financial performance in operating costs as lithium-ion batteries offer higher efficiency, longer lifespan, and greater energy throughput. For comparison, if oil processing were outsourced instead of conducted on-site as per current practice, the NPC, regardless of battery type, would decrease by almost 60%. However, it would still be 170% and 192% (scenarios 3A and 3B respectively) higher than the base case. Additionally, operating costs would increase by 5% compared to scenarios 3A and 3B due to transportation and external processing fees, alongside other logistical challenges. This underscores the potential economic benefits of on-site processing, which could generate additional revenue streams by offering olive oil processing services to other producers.

In terms of GHG emissions, the system operates emission-free, as neither the diesel generator nor the grid is utilised, marking a significant contrast to the base case.

Scenario analysis summary

The proposed scenarios present a structured approach to enhancing energy efficiency and long-term sustainability for the Tunisian case study. Scenario 1 optimises the existing system by eliminating the diesel generator and integrating the solar PV system with the grid to power both the irrigation and borehole pumps, significantly reducing GHG emissions and operating costs, particularly when no additional employee is hired. Scenarios 2 and 3 account for future business expansion, requiring increased irrigation and a more powerful pump to meet higher water demands. While scenario 2 maintains a similar technical setup to scenario 1 with relatively modest investment needs, scenario 3 achieves full energy independence through additional solar PV capacity and battery storage, eliminating grid reliance entirely. This transition, coupled with on-site olive oil extraction, demands a significantly higher investment but enhances long-term resilience and sustainability. Table 21 summarises the key economic and environmental indicators for each scenario in comparison to the base case.

Table 21. Case study 2: Comparison of initial investment, NPC, annual operating costs and GHG emissions between base case and scenarios 1-3

	Initial investment	**NPC**	**Operating costs**	**GHG emissions**
Unit	USD	USD	USD/year	$tCO_{2\text{-}eq}$/year
Base case	12,200	88,000	8,800	20.73
Scenario 1	27,700	40,600	3,300	2.99
Scenario 2	28,000	90,300	7,200	6.53
Scenario 3A	179,900	288,900	12,700	0.00
Scenario 3B	216,700	308,000	10,600	0.00

Notes: All cost figures in USD are rounded to the nearest hundred to enhance readability and facilitate comparison.

Abbreviations: $tCO_{2\text{-}eq}$ = tonne of carbon dioxide equivalent; GHG = greenhouse gas; NPC = net present cost; USD = United States dollar

The selection of the most suitable scenario ultimately depends on the entrepreneur's financial capacity, operational priorities, and long-term vision. Scenario 1 provides a cost-effective optimisation with immediate reductions in operating costs and emissions. Scenario 2 supports future expansion with a manageable investment while maintaining grid connectivity. Scenario 3, though requiring the highest upfront cost, ensures full energy independence, covering future water and energy needs, eliminates grid reliance, and maximises sustainability benefits.

7.3.2.3 MTF evaluation

This chapter evaluates the enhancement scenarios for case study 2, using the World Bank's MTF.

Several assumptions underpin the MTF assessment. Capacity requirements for electric energy sources are already at tier 5 in the base case and scenario 1. In addition to this, scenario 2 experiences an electric demand increase of approximately 37% due to anticipated operational expansion, while scenario 3 sees a 52% increase, stemming from both expanded operations and the introduction of onsite olive oil extraction. The capacity attribute for non-electric demand across all scenarios now achieves tier 5 requirements due to the enhanced solar PV configurations. Availability assumptions indicate high performance, with scenarios 1 and 2 experiencing no unmet load for both electric and non-electric energy supplies, confirmed by the absence of grid outages at the external oil extraction facility. Scenario 3 achieves nearly full availability, with minimal unmet load of around 0.1% from the solar PV system. Reliability aligns with availability results, with scenarios 1 and 2 demonstrating zero outages, while scenario 3 records minimal disruptions amounting to approximately 10 min/week. Affordability varies across scenarios, with scenarios 1 and 2 retaining external oil extraction, thus limiting electric supply affordability to tier 3, although non-electric supply is assumed to meet tier 5 requirements. Scenario 3 is assumed to fully achieve tier 5 affordability, based on the assumption that costs for both electric and non-electric energy from the solar PV system are equal to or lower than existing grid tariffs. Convenience considerations highlight the operational impact differences among

scenarios. For electric supply in scenarios 1 and 2, the convenience rating remains at tier 3 due to ongoing reliance on external oil extraction facilities, which incur additional time, effort, and cost. Scenario 3 improves convenience to tier 5 by moving oil extraction onsite. Regarding non-electric convenience, scenario 1 is moderately rated due to the manual labour required for daily irrigation tasks, despite technological improvements. Scenarios 2 and 3 significantly enhance convenience, achieving tier 5 through employing dedicated personnel for irrigation tasks, thus freeing the entrepreneur to focus on other business priorities. Health evaluations consistently rate all scenarios at tier 5, reflecting the complete elimination of diesel usage and reliance exclusively on clean energy sources (BLEENS). Safety remains unchanged across all scenarios, maintaining consistency with the base case conditions.

Figure 36 presents the progression in energy access tier performance from the base case to enhancement scenarios 1-3 for case study 2, based on the World Bank's MTF. Starting from an overall tier 2 in the base case, scenarios 1 and 2 improve the performance to tier 3, while scenario 3 achieves the maximum attainable tier 5 for both electric and non-electric energy carriers. The primary limitations for scenarios 1 and 2 stem from continued reliance on an external olive oil extraction facility, imposing inconvenience and additional costs on the entrepreneur, along with the persistent manual labour required for irrigation tasks, particularly evident in scenario 1. Notable enhancements across all scenarios are evident in the availability attribute, achieved through system improvements and additional solar PV capacity coupled with battery storage, and significant health attribute improvements due to the complete elimination of diesel usage.

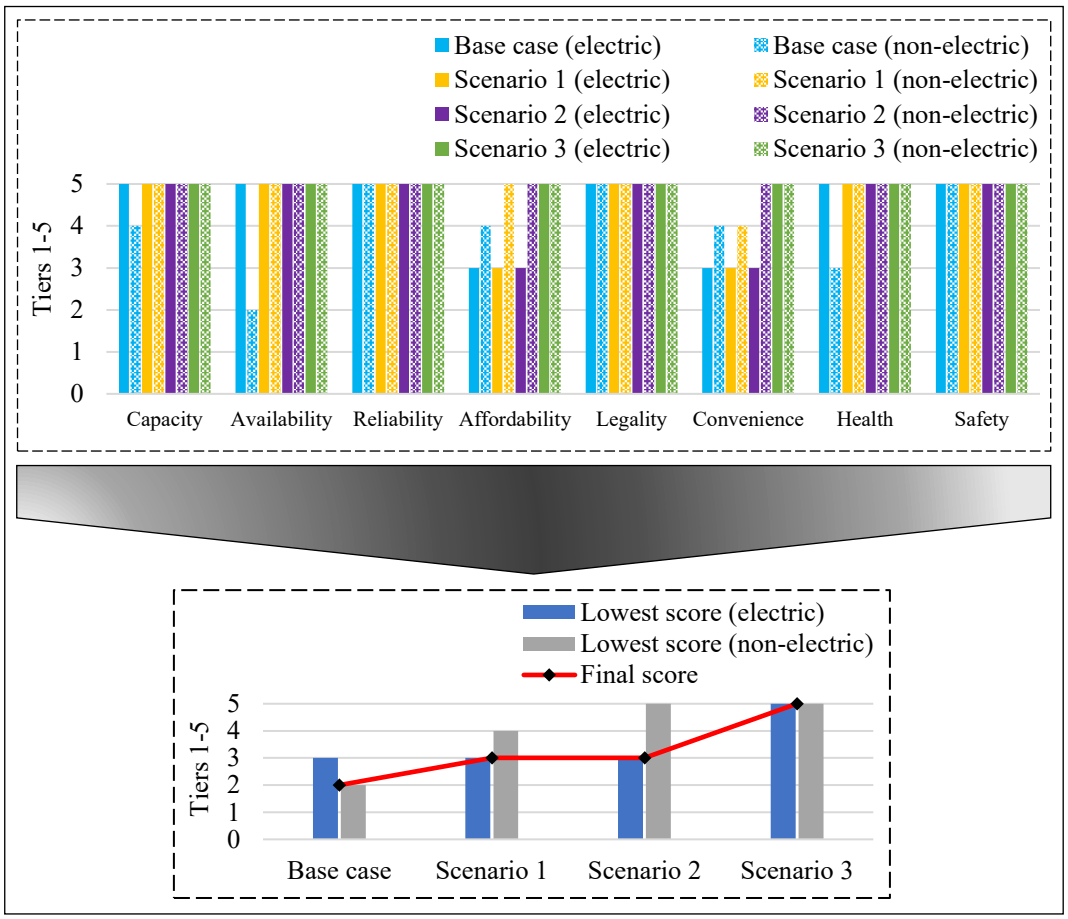

Figure 36. Case study 2: MTF tier performance comparison between base case and scenarios 1-3

These outcomes demonstrate the tangible benefits of transitioning toward comprehensive renewable energy systems. Scenario 3, in particular, exemplifies how full integration of solar PV technology and battery storage can substantially elevate operational convenience, affordability, and overall sustainability. The findings underscore the potential of targeted technological interventions and infrastructural improvements in achieving optimal energy access and productivity gains, significantly contributing to enhanced operational and environmental outcomes.

7.3.3 Case study 3: Kenya – Dairy production and cereal milling

Located in Murang'a County, 70 km from Nairobi, Kenya, this small-sized enterprise is co-owned by a married couple, with operations spanning two separate sites: a dairy plant and a cereal milling facility located several kilometres apart. The

enterprise produces approximately 60 tonnes of dairy products per month, while the cereal milling facility processes around 1,400 tonnes of grains monthly for both human consumption and animal feed. Combining profits from both facilities, an average profit margin of approximately 8% is achieved. Notably, the total energy expenditure from both sites ranges between 6,600 and 6,700 USD/month, with 82% of the costs stemming from the cereal milling facility.

Waste generation is concentrated at the dairy facility, where daily outputs include 60,000 litres of wastewater and nearly 1.6 tonnes of cow manure from a herd of 100 cows (Nennich et al., 2005). The wastewater undergoes treatment at a privately owned facility, while the manure remains untreated. Both waste streams are repurposed for irrigation and fertilisation on the owner's private agricultural land.

The female owner identifies key challenges such as sourcing raw materials, as most of the dairy and cereal ingredients are imported, and rising raw material costs. Gender-related obstacles identified by the female co-owner include limited knowledge of energy systems to enhance operational efficiency.

The entrepreneur is motivated to adopt additional renewable energy technologies for economic savings and environmental sustainability and to address unreliable energy carriers, particularly grid electricity, with outages of over 11 hours per week. However, current obstacles to adopting renewable energy technologies include a lack of access to finance and regulatory uncertainty, coupled with inadequate government support for implementing such new technologies. Her willingness to invest in renewable energy depends on the terms and conditions of the financing options available.

Applying the World Bank's MTF, the enterprise achieves an overall score of 3. This reflects notable limitations, particularly in grid reliability and health impacts associated with the use of biomass briquettes, which, while categorised as a lower-tier energy carrier under the MTF, is somewhat mitigated by the presence of an emissions extractor. Consequently, opportunities for improvement exist in both electricity supply and thermal energy systems.

This contextual background provides the necessary foundation for a deeper analysis of the enterprise's energy conditions. What follows is a detailed assessment of the baseline situation, encompassing the current state of energy access, the techno-economic configuration of existing systems, and the environmental

footprint of ongoing operations, forming a benchmark against which the effectiveness of potential energy enhancement strategies can be evaluated.

7.3.3.1 Base case

The technical setup of case study 3 encompasses two distinct facilities: a dairy plant and a cereal milling facility, located a few kilometres apart. The dairy facility operates an energy-intensive hybrid energy system, where electricity (from the grid and solar PV, with diesel generators acting as backup solutions) powers electrical equipment, as well as cooling and freezing processes. Additionally, a briquette boiler provides thermal energy to supply process heat. In contrast, the cereal milling site relies entirely on grid electricity for milling operations. Table 22 provides an overview of the key productive use applications across both facilities, with particular emphasis on the temperature-sensitive processes integral to dairy production, such as pasteurisation, cooling, and storage.

Table 22. Case study 3: Summary of productive use applications

Process	**Temperature**	**Energy carrier**	**Appliance**		**Power rating or consumption**	
	°C	Type	Count	Type	Value	Unit
Dairy production	10	Grid electricity; Solar PV-based electricity; Diesel-based electricity	2	Controller device	2; 10	kW
	-	Grid electricity; Solar PV-based electricity; Diesel-based electricity	1	Homogeniser	30	kW

	-	Grid electricity; Solar PV-based electricity; Diesel-based electricity	1	Cream separator	7.5	kW
	0	Grid electricity; Solar PV-based electricity; Diesel-based electricity	1	Water chiller	50	kW
	4	Grid electricity; Solar PV-based electricity; Diesel-based electricity	1	Butter churn	6	kW
	4	Briquettes	3	Milk tank	46,200	kg/month
	80-90	Briquettes	1	Cream heater		
	40-90	Grid electricity; Solar PV-based electricity; Diesel-based electricity	1	Pasteuriser	15	kW
Freezing	-5 to 2	Grid electricity; Solar PV-	1	Storage unit	3.5	kW

		based electricity; Diesel-based electricity				
Milling	-	Grid electricity	3	Mill	22; 40; 75	kW
Mixing	-	Grid electricity	1	Mixer	4	kW
Packaging	-	Grid electricity; Solar PV-based electricity; Diesel-based electricity	2	Packaging device	7.5; 20	kW
Sanitation	65-75	Grid electricity; Solar PV-based electricity; Diesel-based electricity	2	Equipment cleaner	3; 7.5	kW

Notes: The solar PV system has an installed capacity of 35.64 kW_p, while the two diesel generators have capacities of 160 kW and 240 kW, respectively.

Abbreviations: °C = degree Celsius; kg = kilogramme; kW = kilowatt; PV = photovoltaic

Mapping the enterprise's thermal and electrical processes in more detail enables a characterisation of its daily energy demand dynamics and operational requirements.

The dairy plant specialises in milk and yoghurt production. Dairy processing requires a seamless interplay between electrical, cooling and heating energy to ensure efficiency, maintain hygiene, and produce high-quality dairy products. Many processing stages depend on electrical energy, as well as heating and cooling, relying on a combination of grid electricity, an on-site PV system, and a biomass-

based briquette boiler. Given the sensitivity of dairy processing to energy disruptions, the facility also employs two diesel generators (240 kW and 160 kW, consuming 25 L/h and 10 L/h, respectively) as backup power sources during grid outages and periods when solar generation is insufficient.

The dairy plant operates 7 days/week. Recognising that some downtime may occur throughout the year due to maintenance or operational adjustments, for modelling purposes, it is assumed to run continuously for 365 days/year. The process begins with the arrival of milk tankers at the reception docks (Food and Agriculture Organization (FAO), 2014), where daily about 3,000 litres of raw milk is collected in cans. The raw milk is sourced from both the facility's own farm and nearby farmers. After being emptied, the milk cans are thoroughly cleaned using a can scrubber, which operates at 3 kW for about 1h/day. To ensure proper storage conditions, a control unit maintains temperature and humidity below 10°C, requiring 10 kW for 1h/day. Once received, the milk is rapidly cooled using a high-capacity water chiller, one of the most energy-intensive components in the facility. Operating at 50 kW for 2h/day, the chiller brings the milk down to 4°C, where it is stored in stainless steel raw milk tanks[11]. This controlled cooling is essential to prevent bacterial growth and maintain the milk's quality before further processing. Filtration follows, ensuring that any impurities are removed (FAO, 2014). This process is powered by a filtration unit consuming 2 kW over 3h/day. Once filtered, the milk moves to the cream separation stage, where it is processed using a cream separator that operates at 7.5 kW for 1h/day. If required by specific product lines, the cream can undergo additional heating at 80-90°C to achieve the desired characteristics. Next, the milk is homogenised, a process that improves texture and prevents fat separation by breaking down fat molecules (FAO, 2014). This step, carried out at 60-65°C, requires 30 kW for 1h/day. This is followed by pasteurisation (FAO, 2014), a critical stage where the milk is heated to 90°C for 10 minutes and then rapidly cooled back to 4°C to ensure safety and extend shelf life. The pasteurisation system, operating at nearly 15 kW for 3h/day, ensures that all microbial risks are eliminated while preserving the milk's natural qualities. The pasteurised milk is then transferred to a dedicated storage tank with a 5,000-liter capacity, maintaining a temperature of 4°C until it is ready for packaging. Currently, packaging is done exclusively in cans, with future plans to introduce alternative packaging formats. Although milk and yoghurt packaging equipment

[11] At the time of the interview, the dairy plant had not yet reached its full operational capacity. The facility is designed to accommodate a daily intake of raw milk, which can be stored in two dedicated milk tanks, each with a capacity of 5,000 L/day.

had already been purchased and installed, they were not yet operational at the time of the interview. Similarly, equipment for butter churning and ripening had been set up but remained unused, indicating potential expansion avenues for the facility in the near future. To maintain strict hygiene standards, equipment cleaning is performed at temperatures between 65-75°C. This process, which consumes 7.5 kW for approximately 2h/day, ensures that all dairy production equipment meets food safety requirements. Once processed and packaged, the dairy products are moved to storage, where temperature control remains critical. A storage units operates between -5°C and 2°C. This cooling storage unit, although technically in operation 24 h/day, functions in cycles, alternating between active cooling and standby mode (Bhatia & Angelou, 2015). To reflect its actual energy consumption, it is estimated to draw power at 3.5 kW for approximately 5h/day.

In contrast, the cereal milling facility is entirely dependent on grid electricity to power its milling machinery and auxiliary equipment. The milling operations take place 5 days/week. The most energy-intensive process is the maize mill, which operates at 75 kW for 12 hours daily from 7:00 to 19:00. The animal feed, hammer mill, and mixer run for 8h/workday from 9-17:00, and have a power rating of 40 kW, 22 kW, and 4 kW, respectively.

A detailed breakdown of equipment power ratings in kW, average daily operating hours, and specific usage patterns for both facilities is provided in Appendix D. These data serve as the basis for modelling the hourly demand profiles and evaluating the overall techno-economic configuration of the system.

According to data collected during the interview (Gad & Leone, 2025), the dairy plant is estimated to source approximately 3,000 kWh per month from the national electricity grid, accounting for 45% of the electricity obtained from the grid and solar PV combined. The remaining 55% is supplied by a rooftop solar PV system with a total installed capacity of 35.64 kW_p (comprising two subsystems of 29.16 kW_p and 6.48 kW_p) and a 25-kW inverter. To verify these estimates, HOMER Pro modelling was conducted to simulate the plant's energy production and consumption based on the installed PV system and local solar resource data. The HOMER Pro model estimates that the dairy plant's actual electricity consumption from solar PV, after conversion losses, amounts to an average of 3,302 kWh/month. Additionally, according to HOMER Pro estimates, approximately 13% of the total solar PV generation, over 1,100 kWh per month, is curtailed, meaning it is generated but remains unused due to a lack of immediate demand, storage capacity, or a net metering scheme. Grid consumption is estimated at 3,450 kWh/month.

These modelled estimates are used in the analysis as they closely match the interview-based approximations. Moreover, two diesel generators consume together around 120 L/month, corresponding to 359 kWh/month, to accommodate for times of demand with grid outages and when solar energy does not suffice. The diesel demand is estimated based on an LHV of 43 MJ/kg, a fuel density of 0.84 kg/L, and an average generator efficiency of 30% (Garg et al., 2006; Stiel & Skyllas-Kazacos, 2012). Based on these figures, the total annual electric demand (including cooling needs) of the dairy facility is estimated at 84,308 kWh/year.

The dairy plant's thermal (heating) energy demand is exclusively met by a biomass briquette-fuelled boiler. The facility consumes approximately 1.5 m^3 of briquettes per day (Gad & Leone, 2025), which, when considering briquette density and boiler efficiency, translates to an estimated annual requirement of approximately 554 tonnes/year to generate the necessary 1,562 MWh/year of thermal energy. As the specific composition and density of the briquettes used remain unknown, FAO average values have been applied, recognising that briquetting is a densification process that increases the low bulk density of biomass (typically 150-200 kg/m^3) to a higher density range of 900-1300 kg/m^3 (Branca et al., 2014a). An estimated density of 1,100 kg/m^3 is also in line with other scientific literature values (Bhagwanrao & Singaravelu, 2014). The boiler is assumed to operate at an efficiency of 65%, an estimate informed by studies indicating briquette boiler efficiencies generally fall within the range of 60-70% (Jasinskas et al., 2012; Kanase et al., 2021; Nikiforov et al., 2024).

The electrical and cooling demand at the cereal milling facility is estimated based on energy consumption and equipment capacity, yielding a daily demand of 1,428 kWh from Monday to Friday. This corresponds to annual grid purchases of 371,280 kWh/year. The full technical setup at both facilities is presented in Figure 37.

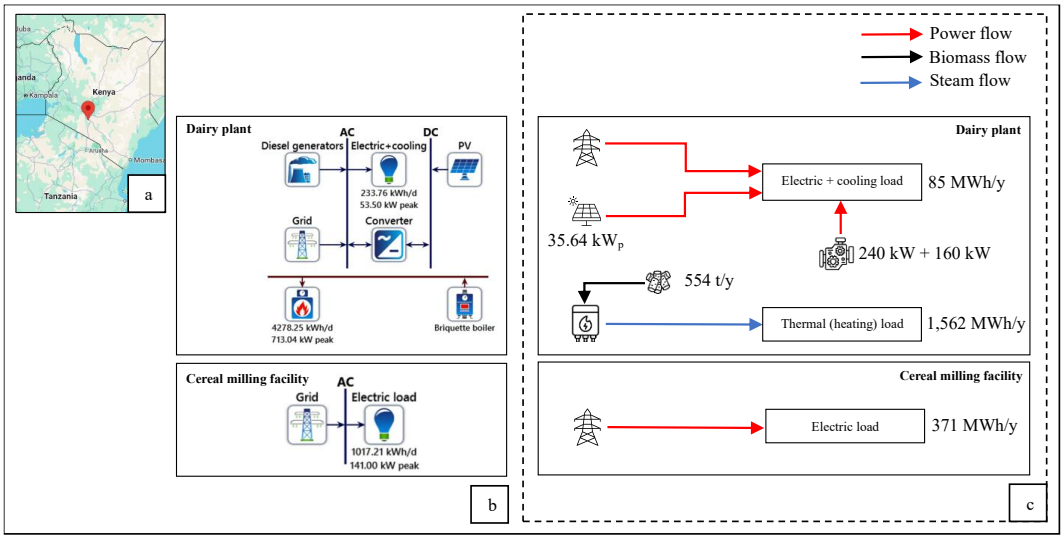

Figure 37. Case study 3: Technical setup of the base case

Notes: a) Geographic location, source: google.maps; (b) Technical setup designed using HOMER Pro; c) Technical setup designed by the author.

Abbreviations: kW = kilowatt; kWh/d = kilowatt-hour per day; kWh/y = kilowatt-hour per year; kW_p = kilowatt peak; MWh/y = megawatt-hour per year; t/y = tonne per year

From an economic perspective, it is assumed that the enterprise has no outstanding loans for equipment or energy systems. The economic analysis considers specific cost components, including diesel fuel, briquette purchase costs, and grid electricity on the one hand and O&M and replacement costs of various systems on the other hand. For diesel fuel, no replacement costs are accounted for, as the generators are assumed to have a lifespan of 20,000 hours each, with only approximately 82 hours of combined operation expected per year. Given this limited use, replacement within the 25-year assessment period is not considered necessary. However, O&M costs are included, based on HOMER's standard assumption of 0.03 USD/kWh per operating hour. For grid electricity costs, the economic assessment was based on the estimated electricity consumption at both facilities, evaluated using the applicable grid tariff of 17.68 USD/kWh (EPRA, 2023; KPLC, 2023). When compared to the reported electricity expenses obtained from the interview (Gad & Leone, 2025), a slight discrepancy of 1% was observed, with the interview data showing a marginally higher cost. However, this variance is considered acceptable, and the calculated values remain the basis for the analysis. The O&M costs for the solar PV system are assumed to follow a standard industry value of 10 USD/kWp of installed capacity (ESMAP, 2022).

Regarding the biomass boiler, in addition to the cost of briquette purchases, O&M expenses are considered. Fixed O&M costs are estimated at 3-6% of the boiler's CAPEX per year, while variable O&M costs are accounted for in USD/MWh produced, in alignment with IRENA estimates (IRENA Secretariat, 2012). Equipment replacement is also factored into the economic analysis. The solar PV inverter is assumed to require replacement after 15 years, while the biomass boiler is expected to be replaced after 20 years, with both retaining a salvage value. The 20-year boiler replacement period follows IRENA's recommendation. Although some sources suggest efficiency declines after 11-12 years, with replacement recommended within that timeframe (Stolarski et al., 2020; Teplická et al., 2020), IRENA's estimate is used for consistency. The replacement cost is also based on IRENA's assessment, which provides an average cost of 3,070 USD/kW across different biomass briquette boiler technologies (IRENA Secretariat, 2012).

At a project lifetime of 25 years and assuming a 6.9% nominal discount rate, in line with IRENA's CoC (Taylor et al., 2023) and similar to other studies using a discount rate between 5-11% (Katche et al., 2024; Pueyo et al., 2016), the project results in an NPC of 2,464,833 USD and operating costs of 209,607 USD/year. As indicated in Table 23, the majority of costs stem from O&M of the briquette boiler (50% of NPC) at the dairy plant, followed by grid electricity purchases at both facilities, accounting for 35% of the NPC, while 11% is attributed to boiler replacement (after deducting its salvage value). The remaining minimal costs arise from briquette and diesel fuel use, with negligible contributions from O&M of the solar PV system.

Table 23. Case study 3: Net present cost and operating costs of the base case

Component	NPC (USD)	Operating costs (USD/year)	Share of NPC (%)
Energy carrier			
Diesel	20,253	1,722	<1%
Briquettes	69,619	5,920	3%

Grid electricity	854,279	72,647	35%
O&M			
Diesel generators	11,532	981	<1%
Briquette boiler	1,236,413	105,143	50%
Solar PV	4,191	356	<1%
Replacements			
Briquette boiler	576,367	49,014	23%
Inverter	2,205	188	<1%
Total salvage value	-310,028	-26,364	-13%
Total	**2,464,833**	**209,607**	**100%**

Notes: A nominal discount rate of 6.9% is applied, and the project lifetime is set for 25 years. Due to rounding, the sum of individual items may not exactly match the total.

Abbreviations: % = percent; NPC = net present cost; O&M = operation and maintenance; USD = United States dollar

To situate the enterprise's techno-economic profile within a broader sustainability framework, an environmental impact assessment was undertaken. This involved calculating both direct and indirect GHG emissions across scope 1 (direct emissions from fuel combustion) and scope 2 (indirect emissions from grid electricity use), in line with the guidelines set by PCAF (2020, 2022) and the UNFCC Secretariat (2021). Other GHG emissions, such as those associated with transportation related to business operations (e.g., employee or owner commuting), are not included in this analysis. Additionally, the use of biomass briquettes is not considered under scope 1 emissions, as it is assumed that they are sustainably sourced, follow a short-term carbon cycle, and any other gases emitted during combustion are neglected (Rypdal & Paciornik, 2006). Furthermore, the presence of a smoke extractor reduces the environmental impact of briquette use.

The total emissions for the base case amount to 133.92 $tCO_{2\text{-}eq}$/year, with 97% of these emissions originating from scope 2, primarily due to grid electricity consumption at the cereal milling facility. The diesel generators, which serve as backup solutions, contribute only 3.64 $tCO_{2\text{-}eq}$/year. Specifically, the cereal milling facility emits 117.72 $tCO_{2\text{-}eq}$/year, accounting for 90% of scope 2 emissions and approximately 88% of the total emissions in this case study. Furthermore, when considering the enterprise's production output, its GHG emissions are equivalent to 0.09 $tCO_{2\text{-}eq}$/tonne of goods produced.

These findings underscore critical gaps, especially in the reliability of electricity supply and the health-related implications of current thermal energy practices. While some mitigating measures are already in place, such as the emissions extractor for briquette combustion, the enterprise's overall tier 3 MTF score signals that substantial room for improvement remains. The following analysis explores targeted enhancement scenarios designed to address these shortcomings by advancing both the quality and sustainability of energy services for case study 3.

7.3.3.2 Scenario analysis

This analysis evaluates four progressive enhancement scenarios designed to guide both the dairy plant and the cereal milling facility toward complete reliance on renewable energy.

At the dairy plant, scenarios 1 and 2 specifically address enhancements to electrical and cooling systems while maintaining the existing biomass briquette boiler for thermal energy demands. Conversely, scenarios 3 and 4 shift the focus toward sustainable thermal solutions by exploring replacements for the briquette boiler. It should be noted that for all enhancement scenario assessments at the dairy plant, a fundamental adjustment was made by assuming an increase in electricity demand at the dairy facility. However, this increase is based solely on the immediate and highly probable utilisation of existing equipment. While the enhancement scenarios consider a 25-year project lifetime, during which production and energy demand could be expected to rise, the analysis does not account for future expansions beyond the activation of these existing assets. Specifically, the assessment incorporates equipment that has already been purchased and installed but was not in operation under the base case scenario, as indicated by interview data (Gad & Leone, 2025). This includes the butter churn and ripening unit (6 kW capacity), as well as the yoghurt and milk packaging

devices (7.5 kW and 20 kW capacities, respectively). The inclusion of this equipment leads to a 27% increase in electricity demand compared to the base case. The assumed daily operation of the additional equipment is based on expected usage patterns communicated during the interview (Gad & Leone, 2025). The butter churn and ripening unit is expected to operate once the primary milk processing activities have been completed, specifically between 15:00 and 16:00. Packaging occurs at the final stage of the value chain, with milk packaging taking place between 16:00 and 17:00, while yoghurt packaging requires a longer duration of approximately five hours, running from 16:00 to 21:00. Given these assumptions, it is likely that certain productive use activities extend beyond the facility's usual working hours, reflecting the operational flexibility required to accommodate different processing stages.

Regarding the cereal milling facility, two main enhancement scenarios are examined: Scenario 1 investigates the potential of net metering coupled with solar PV, while scenario 2 advances further, establishing complete electrical autonomy through solar PV paired with battery storage. For scenarios 3 and 4, the cereal milling facility retains this autonomous configuration, identical to scenario 2. To systematically evaluate the impact of battery storage technologies, each scenario is subdivided into two versions: sub-scenarios "A" consistently employ lead-acid batteries, whereas sub-scenarios "B" utilise lithium-ion batteries.

Scenario 1 initiates the renewable energy transition by evaluating the potential of implementing solar PV combined with net metering. This scenario primarily optimises electricity consumption patterns without drastically altering the existing energy infrastructure. Specifically, the cereal milling facility gains additional solar PV capacity to maximise benefits from net metering, while the dairy plant retains its existing energy arrangement, including the current solar PV system and diesel backup generator. Importantly, the thermal (heating) requirements at the dairy plant remain identical to the base case scenario, ensuring a consistent point of comparison for subsequent scenarios.

Scenario 2 builds upon the renewable energy foundation established in scenario 1 by introducing battery storage technology, achieving complete autonomy from grid electricity and diesel fuel. This advancement transforms both the dairy plant and cereal milling facility into fully autonomous systems, with electrical and cooling demands met exclusively by solar PV paired with battery storage. At the dairy plant, additional solar PV capacity is introduced to offset the removal of grid electricity, while the existing biomass briquette boiler continues to meet the thermal

energy needs. Notably, the diesel backup system is completely removed, signalling a critical shift towards full renewable energy reliance. Similarly, the cereal milling facility transitions to a fully independent system powered entirely by solar PV and battery storage. This scenario further examines the comparative techno-economic impacts through two sub-scenarios: scenario 2A, employing lead-acid batteries, and scenario 2B, integrating lithium-ion batteries.

In scenario 3, building on the complete electrical autonomy achieved in scenario 2, the dairy plant undergoes comprehensive electrification by replacing the existing biomass briquette boiler with a high-temperature industrial heat pump. This transition significantly elevates the electrical energy demand at the dairy plant, thereby requiring further expansion of solar PV and battery storage capacities. The cereal milling facility retains the fully autonomous setup established in scenario 2, with no additional changes made. Consistent with the methodological approach, scenario 3 is again divided into sub-scenarios 3A and 3B to evaluate the implications of different battery technologies (lead-acid vs. lithium-ion) on system performance, autonomy, and economic feasibility.

Scenario 4 introduces yet another advanced approach to enhancing sustainability at the dairy plant by replacing the biomass briquette boiler with a biogas boiler, powered entirely by biogas produced onsite via anaerobic digestion (AD) of cow manure. Before combustion, the biogas undergoes minimal purification to remove impurities such as hydrogen sulphide and moisture, ensuring suitability for boiler usage. Currently, the dairy facility lacks formal manure treatment; instead, manure is directly channelled to agricultural fields through underground piping. Introducing an AD system not only efficiently utilises manure by generating renewable thermal energy but also yields digestate, a nutrient-rich organic fertiliser beneficial to farm economics and environmental management. The cereal milling facility maintains the autonomous energy configuration established in scenario 2. Scenario 4, like previous scenarios, includes sub-scenarios 4A (lead-acid batteries) and 4B (lithium-ion batteries), enabling consistent assessment of how battery technology choices influence overall techno-economic performance.

Across all four scenarios, the systematic introduction of renewable technologies and sustainable practices illustrates a clear progression toward environmental sustainability, economic resilience, and operational independence. In the following sections, each scenario will be discussed in more detail.

Scenario 1: Solar PV with net metering

Scenario 1 assumes the adoption of Kenya's newly introduced net metering scheme at both production sites: the dairy processing plant and the cereal milling facility. Under this policy, enterprises generating excess electricity from renewable sources can export surplus energy to the national grid in exchange for credits, which are deducted from their monthly electricity bills. The technical setup at both sites remains unchanged from the base case; only the billing structure shifts to account for energy exported through net metering.

This scenario is grounded in the 2024 Energy (Net Metering) Regulations, which operationalise the legal framework established by the Energy Act of 2019 (Kenya Law & Laws Africa, 2024; The Parliament of Kenya, 2019). The scheme allows residential users to install systems of up to 4 kW (single-phase) or 10 kW (three-phase), while commercial and industrial users may scale up to 1 MW, depending on their peak demand. Under the net metering model, 50% of the exported energy is credited and deducted from the grid electricity consumption when determining the user's final bill. Surplus credits can be rolled over within the financial year but are forfeited if unused by the end of the year.

The introduction of net metering marks a significant step in Kenya's evolving energy transition strategy, particularly as it aims to increase decentralised renewable energy uptake. However, its implementation is not without complications. From a utility perspective, the Kenya Power and Lighting Company (KPLC) faces financial risks, as increased self-generation reduces electricity purchases while fixed grid maintenance costs remain unchanged (Gatuyu, 2024). Technically, absorbing large volumes of intermittent solar generation may also challenge grid stability, necessitating costly infrastructure upgrades that the utility is not well-positioned to fund.

For enterprises, net metering offers a compelling opportunity to increase the economic viability of solar PV investments. Yet uncertainty around eligibility and long-term regulatory continuity persists. The current regulatory cap limits total programme participation to 100 MW over the first five years (Kenya Law & Laws Africa, 2024), raising questions about future availability. Moreover, while this analysis assumes policy continuity over a 25-year system lifetime, the possibility of revisions or policy reversals presents an additional layer of risk for long-term energy planning.

Scenario 1 is modelled using HOMER Pro software, simulating site-level performance and energy costs under Kenya's current grid tariff of 0.1768 USD/kWh (EPRA, 2023; KPLC, 2023). The purchased energy from the grid is subtracted by 50% of the energy sold to the grid, and this net energy is then multiplied by the grid tariff to determine the final energy cost. The results are intended to illuminate whether net metering, despite its regulatory and structural uncertainties, offers a technically sound and economically advantageous pathway for case study 3. The detailed system configurations for each facility are presented in Figure 38.

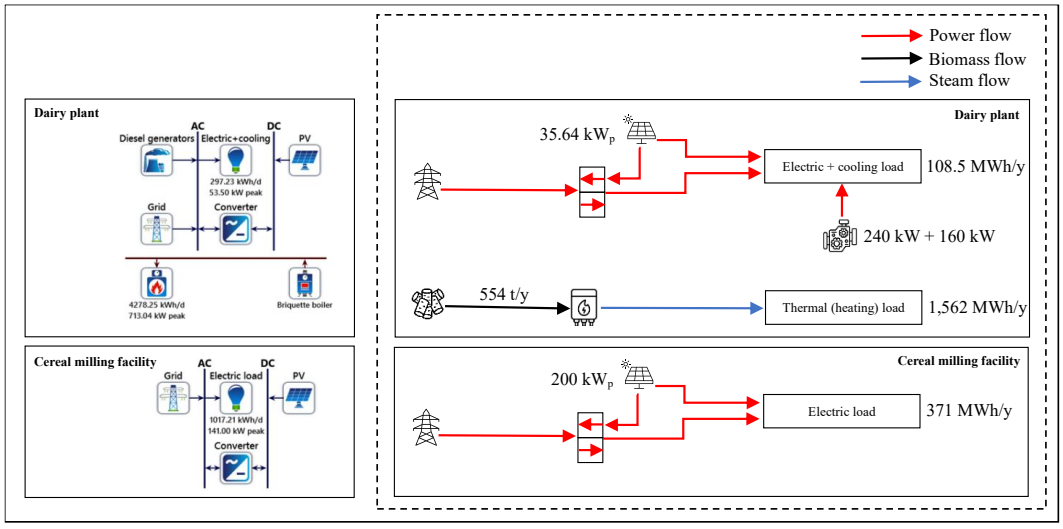

Figure 38. Case study 3: Technical setup of scenario 1

Abbreviations: kW = kilowatt; kWh/d = kilowatt-hour per day; kW_p = kilowatt peak; MWh/y = megawatt-hour per year; PV = photovoltaic; t/y = tonne per year

For the dairy plant, the thermal demand remained unchanged to the base case which is why it will not be discussed further in scenario 1. The electric load profile was adjusted to account for the use of additional equipment, resulting in an increased annual electric energy demand of 108,489 kWh/year, which represents a 27% rise compared to the base case. The energy demand is met through a combination of sources: solar PV, grid electricity, and diesel generators. However, the proportion of energy supplied by each source has shifted compared to the base case. Under the net metering setup, 9,314 kWh/year of previous excess solar PV generation is now fed into the grid. Additionally, a portion of the previously curtailed solar production is utilised to meet the increased energy demand, with the solar PV system supplying 44,746 kWh/year for productive use. Due to the increased load, specifically needed during the evening, grid purchases have

increased to 59,435 kWh/year, while diesel generator use is assumed to remain constant at 4,308 kWh/year. The net energy charged for grid electricity, after accounting for energy sold back to the grid, is 54,778 kWh. Scenario 1 results in a 38% increase in electricity costs compared to the base case. However, when compared to a base case scenario with the same increased load but without net metering, the introduction of net metering results in a 9% decrease in grid electricity costs. This indicates that net metering at the dairy plant offers financial benefits with minimal energy system changes.

At the cereal milling facility, a solar PV system was modelled using HOMER Pro, with net metering capability integrated into the analysis. The system design balanced the costs of the solar PV array and inverter with the potential financial benefits of net metering. The most beneficial setup identified was a 200 kW_p solar PV system coupled with a 160-kW inverter. In this configuration, 209,597 kWh/year is generated by the solar PV system, supplying the demand directly, with 161,684 kWh/year purchased from the grid, representing a 57% reduction in grid electricity purchases compared to the base case. The solar PV system also sells 93,091 kWh/year of excess energy to the grid. This net metering setup at the cereal milling facility results in an 81% grid cost reduction compared to the base case. Combining energy generated for demand and export from solar PV, the system achieves a renewable energy fraction of 65%. The system produced minimal excess electricity of 0.2% of the total solar PV output, with less than 720 kWh/year being curtailed. This level of curtailment is considered negligible and does not significantly impact overall system performance. The design effectively balances generation capacity, cost considerations, and the benefits of the net metering scheme, ensuring high utilisation of the solar PV system while minimising unnecessary oversizing and curtailment losses.

To evaluate the economic viability of scenario 1, key modifications were made to the base case. At the dairy facility, an additional 25 kW inverter was incorporated to maximise the use of excess solar PV generation and facilitate energy export to the grid. However, since the facility already had extra inverters beyond the required 25 kW, it was assumed that two inverters, totalling 50 kW, are now operational without incurring initial costs, with only a replacement cost of 240 USD/kW considered after 15 years (ESMAP, 2022). At the cereal milling facility, the purchase of a new inverter was factored into total solar PV CAPEX. The reported hardware cost for solar PV systems in Kenya is 834 USD/kW_p (Energy Sector Management Assistance Program (ESMAP), 2022). According to the Energy Sector Management Assistance Programme (2022), on average, hardware

represents 15.8% of total mini-grid costs, while installation accounts for 16.8% and soft costs, including permitting and project development, contribute 17.8%. Using these proportions, the total system CAPEX is estimated at 2,634 USD/kW_p. This estimate aligns with other references, though it is on the higher end, as another study in Kenya estimated costs at approximately 2,200 USD/kW_p (Ayora et al., 2023). Both facilities require a bidirectional meter for net metering, which is assumed to cost 278 USD/unit based on scientific literature, with no replacements considered (Roux & Shanker, 2018).

Over a 25-year project lifespan and at a discount rate of 6.9%, scenario 1 results in an NPC of 2,528,213 USD and operating costs of 170,151 USD/year. Despite the increased electricity demand at the dairy facility, the NPC and operating costs see only a modest increase of 3% compared to the base case. The majority of costs still originate from boiler O&M, which accounts for 49% of total expenditures. The CAPEX for the solar PV system at the cereal milling facility constitutes 21% of the total NPC, with boiler replacement costs contributing 11% after deducting its salvage value. Grid electricity costs have been significantly reduced, now making up only 14% of total costs, representing a 59% decrease compared to the base case. This underscores the financial benefits of net metering under Kenya's current regulatory framework. Other cost components contribute minimally, with briquette consumption accounting for 3% and the remaining categories representing between 0% and 1.5% of total NPC.

To evaluate the environmental impact of scenario 1, both scope 1 and scope 2 emissions were assessed. Scope 1 emissions remain unchanged compared to the base case, as diesel generator usage at the dairy facility remains constant. However, scope 2 emissions have decreased by 46%, now amounting to 70.11 $tCO_{2\text{-}eq}$/year, due to the reduced reliance on grid electricity. This reduction was calculated using a conservative approach, where emissions are based on total grid electricity purchased rather than net electricity (imported minus exported), ensuring alignment with GHG Protocol guidelines (Sotos, 2016). Scope 2 emissions continue to represent the majority of total GHG emissions, accounting for 95% of the overall footprint, with the cereal milling facility contributing 73% of these emissions. Furthermore, the GHG emission intensity per unit of production has improved, now reaching 0.05 $tCO_{2\text{-}eq}$/tonne of goods produced, highlighting the environmental benefits of integrating on-site solar PV generation under the net metering scheme.

Scenario 2: Solar PV with battery storage for grid independence and biomass briquettes for thermal demand

Building upon the setup of scenario 1, scenario 2 replaces grid reliance and net metering with battery storage, creating a fully autonomous energy system. This transition entails significant changes in energy management for both the dairy plant and the cereal milling facility. At the dairy plant, additional solar PV capacity is required to compensate for the absence of grid electricity, while the existing briquette boiler remains unchanged to meet thermal energy needs. Notably, the diesel backup system is eliminated, making the dairy plant fully dependent on solar PV and battery storage. Similarly, at the cereal milling facility, grid electricity is replaced with solar PV and battery storage, resulting in a fully autonomous energy system.

To evaluate the techno-economic performance of different battery technologies, scenario 2 is divided into two sub-scenarios. Scenario 2A employs lead-acid batteries for energy storage at both sites, while Scenario 2B integrates lithium-ion batteries instead. This comparative approach allows for an assessment of the technological and economic trade-offs between the two battery types, considering key parameters such as capital costs, efficiency, depth of discharge, and lifespan. The capital cost assumptions for the solar PV system remain unchanged from scenario 1. For battery storage, lead-acid batteries are priced at 142 USD/kWh, based on ESMAP data for Kenya, whereas lithium-ion battery costs are assumed to be 455 USD/kWh, drawing from ESMAP's regional averages for Africa and Asia, due to the lack of Kenya-specific data (Energy Sector Management Assistance Program (ESMAP), 2022). Battery lifespan is estimated based on energy throughput, a standard approach in the literature. Lead-acid batteries sustain approximately 800 kWh of throughput with 60% DoD and 80% efficiency, providing 384 kWh of usable energy before replacement. Lithium-ion batteries last significantly longer, with 3,000 kWh of throughput, 80% depth of discharge, and 90% efficiency, yielding 2,160 kWh of usable energy. Considering real-world factors like temperature, cycling, and maintenance, a conservative lifespan of 5 years for lead-acid and 10 years for lithium-ion batteries is assumed, consistent with scientific literature (Kebede et al., 2021; C. Zhang et al., 2017).

System modelling using HOMER Pro yielded specific technical configurations for both sub-scenarios. In scenario 2A, the dairy plant requires a 200 kW_p solar PV system coupled with 670 kWh of lead-acid battery storage, while the cereal milling facility demands an 810 kW_p solar PV system alongside 4,100 kWh of lead-acid

battery capacity. In scenario 2B, the dairy plant requires a slightly higher PV capacity of 250 kW_p, but due to the superior performance of lithium-ion batteries, only 260 kWh of storage is needed. At the cereal milling facility, 840 kW_p of solar PV and 2,800 kWh of lithium-ion battery storage are required. Both sub-scenarios utilise a 75-kW inverter at the dairy plant and a 150-kW inverter at the cereal facility. As in scenario 1, it is assumed that existing inverters at the dairy plant can be repurposed, given that the facility owner originally purchased four 25-kW inverters, of which only one is required in the base case. In contrast, for the cereal milling facility, appropriately sized inverters must be newly acquired. The complete technical system setup for scenario 2 is presented in Figure 39.

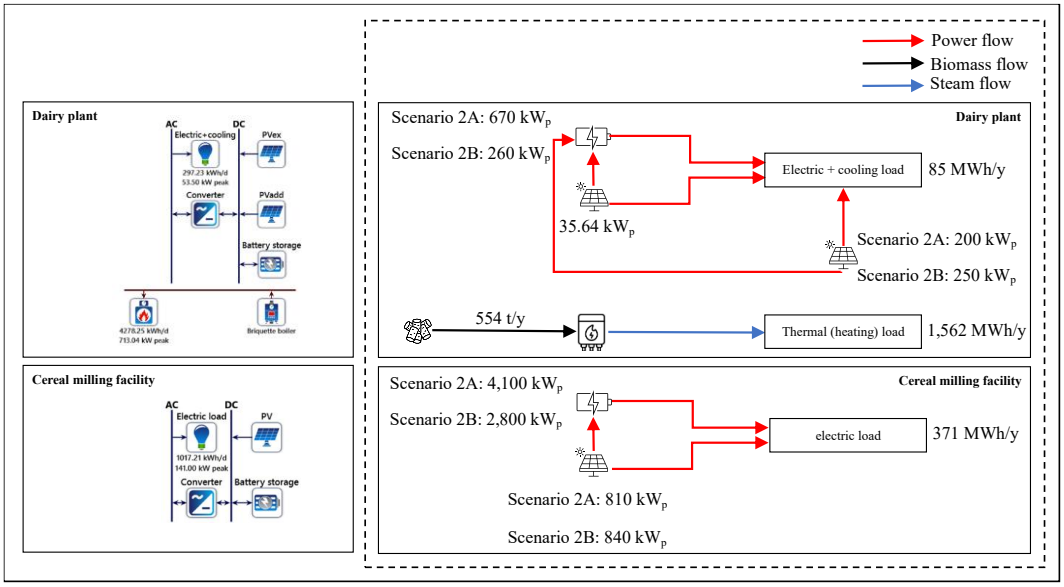

Figure 39. Case study 3: Technical setup of scenario 2

Notes: The left graphic was modelled with HOMER Pro, and the right graphic was modelled by the author. Scenario 2A contains lead-acid battery storage, while scenario 2B contains lithium-ion battery storage.

Abbreviations: kW = kilowatt; kWh/d = kilowatt-hour per day; kWh/y = kilowatt-hour per year; kW_p = kilowatt peak; MWh/y = megawatt-hour per year; PV = photovoltaic; PV_{add} = additional photovoltaic system; PV_{ex} = existing photovoltaic system; t/y = tonne per year

Both sub-scenarios under scenario 2 achieve complete reliance on renewable energy, as the electrical supply at both the dairy and cereal milling facilities is now met entirely by solar PV and battery storage, while thermal demand is covered 100% by sustainably sourced biomass briquettes. With no changes to the thermal energy system, the focus remains on electricity generation and storage. Given that

solar PV and briquettes are considered renewable energy sources, both facilities attain a 100% renewable energy fraction. The solar PV and battery systems successfully cover the electrical demand, with only minimal unmet demand, less than 0.1% of the total energy needs, ensuring near-total electrification of operations. At the dairy plant, unmet demand remains around 100 kWh/year, while at the cereal milling facility, it is approximately 360 kWh/year, an insignificant fraction of overall energy consumption.

The lead-acid battery system in scenario 2A contributes to 14% of the total electricity demand at the dairy plant, storing and discharging 15,434 kWh/year, while at the cereal milling facility, it accounts for 11% of demand, delivering 39,071 kWh/year. The lead-acid system offers an autonomy of approximately 33 hours at the dairy plant and 58 hours at the cereal facility, meaning it can operate without solar input for more than one and two full days, respectively. Similar to sub-scenario 2A, lithium-ion batteries contribute 13% of total demand at the dairy plant by storing and discharging 14,193 kWh/year, and 10% at the cereal milling facility, with 37,743 kWh/year. Due to its smaller storage size, the lithium-ion batteries offer reduced autonomy, with 17 hours at the dairy plant and 53 hours at the cereal milling facility.

While the installed PV capacity ensures reliability and resilience, it also leads to significant curtailment, as surplus energy cannot be effectively stored or utilised, highlighting inefficiencies in system design. Scenario 2A, which employs lead-acid batteries, results in excess electricity of 69% at both locations, equivalent to 258,327 kWh/year at the dairy facility and 893,104 kWh/year at the cereal milling facility. This surplus arises primarily due to the mismatch between generation and demand, the limited battery storage capacity, and the operational schedules of the facilities. In scenario 2B, where lithium-ion batteries are used, excess electricity remains even higher than in 2A, accounting for 75% (340,438 kWh/year) at the dairy facility and 71% (946,584 kWh/year) at the cereal milling facility. A potential optimisation would be increasing battery storage capacity to store more solar energy for later use, particularly at the dairy plant where night-time demand exists. However, this would substantially increase costs, potentially making the system less economically viable. While alternative demand-side measures, such as introducing additional flexible loads, like pre-cooling storage at the dairy plant or dynamically scheduling milling operations, could decrease the need for oversized PV and battery systems, their implementation would require careful assessment of operational flexibility and entrepreneurial willingness, which is beyond the scope of this study. Another alternative approach could be exploring additional uses for

excess electricity, such as selling power under a net metering scheme or integrating energy-intensive operations to absorb the surplus. Scenario 1 considered net metering as a means to avoid investment in battery storage, and a combined approach utilising solar PV, battery storage, and net metering could be assessed in future studies. It is important to note that increasing unmet demand was not considered a viable option to reduce excess electricity produced by the solar PV system, as the primary objective of this study is to enhance energy access and ensure a reliable electricity supply for productive use. Reducing outages and mitigating energy-related disruptions to production were key priorities, necessitating a system design that prioritises meeting demand while maintaining economic feasibility.

From an economic perspective, scenario 2B incurs a 6% higher NPC than scenario 2A but reduces operating costs by 14%, reflecting the trade-off between upfront investment and long-term operational savings. The initial CAPEX in scenario 2B is 28% higher than in 2A, primarily due to the costlier lithium-ion battery technology and increased solar PV capacity. Compared to the base case, NPC increases by 171% in scenario 2A and 186% in scenario 2B, with operating costs rising by 42% and 21%, respectively. Despite the significant upfront investment, both scenarios eliminate grid electricity, as well as diesel fuel and diesel O&M costs, with scenario 2B particularly benefiting from lower long-term maintenance expenses. In both sub-scenarios, solar PV CAPEX constitutes the largest cost component, accounting for 38% of NPC. In scenario 2A, the second-largest expense is battery replacement costs (19%), followed by lead-acid CAPEX (10%) and battery O&M (8%). Scenario 2B, in contrast, sees lithium-ion CAPEX as the second-largest cost (20% of NPC), followed by replacement costs (15%), while battery O&M is significantly lower at 5% of NPC, reflecting the reduced maintenance requirements of lithium-ion technology. Boiler O&M and replacement costs remain consistent across both sub-scenarios, contributing 18-19% and 8-9% of NPC, respectively. Briquette fuel expenses are minimal, accounting for only 1% of NPC in both cases. Salvage values from major equipment, including the boiler and, in scenario 2B, lithium-ion batteries, along with minor contributions from inverters, help offset overall costs. These values account for 5% of NPC in scenario 2A and nearly 7% in scenario 2B, offering a modest reduction in total system costs.

From an environmental standpoint, scenario 2 is entirely emissions-free, as both facilities rely exclusively on solar PV and sustainably sourced biomass briquettes. With the complete elimination of grid electricity and diesel backup, scope 1 and scope 2 emissions are reduced to zero, demonstrating the viability of a fully renewable, off-grid energy solution for both facilities.

Scenario 3: Achieving complete electrification with solar PV and battery storage

In scenario 3, the existing biomass briquette boiler at the dairy plant, currently supplying steam at temperatures up to 90°C, is replaced by a high-temperature industrial heat pump to achieve complete electrification (Monschauer et al., 2022). Industrial and high-temperature heat pumps are well-established for process temperatures below 100°C and offer significant efficiency advantages over conventional heating methods (Hamid et al., 2023). A heat pump operates by transferring heat from a lower-temperature source to a higher-temperature sink using electricity (Monschauer et al., 2022). Unlike conventional electric heating, heat pumps achieve high efficiencies by moving existing heat rather than generating it directly. This efficiency is expressed as the coefficient of performance (COP), which often exceeds 3, particularly when the temperature lift, the difference between input and output temperatures, remains within the 30-50°C range (Hamid et al., 2023; Monschauer et al., 2022). For larger temperature lifts, the COP tends to decline, though a heat pump can be configured in a way that limits the loss of efficiency, such as by incorporating intermediate heat exchangers or cascaded cycles (Monschauer et al., 2022). In a cascaded configuration, the heat pump operates as two single-stage cycles coupled together by a cascade heat exchanger. However, such modifications significantly increase system costs, making them less economically viable in many industrial applications. In this scenario analysis, to reduce the temperature lift requirement and enhance the COP to values of 4 or higher, a waste heat source, namely the condenser heat from the existing air-cooled water chiller, is utilised and integrated with the heat pump system (Hamid et al., 2023). Given Murang'a County's moderate ambient temperatures (Ayugi & Tan, 2019; Climate Centre & Kenya Red Cross, 2022), both air-source and water-source heat pumps are technically feasible[12]. However, to optimise performance and reliability, integration with the existing cooling system via a water-to-water heat

[12] Mechanical vapour recompression (MVR) technology, like heat pumps, uses electricity to upgrade heat to higher temperatures and shows promise for future industrial heating applications (Monschauer et al., 2022). However, its adoption remains less established than high-temperature heat pumps, which have a proven track record for process temperatures below 100°C. Given their reliability and seamless integration, heat pumps are the preferred solution for the dairy plant's electrification and efficiency optimisation.

pump is preferred, as it enables stable operation and greater energy efficiency (Hamid et al., 2023; Monschauer et al., 2022).

The required heat pump capacity was estimated based on an annual thermal energy demand of 1,561,560 kWh/year, distributed over an operational schedule of 8 hours per day throughout the year. This results in a required thermal output capacity of approximately 535 kW. Assuming a COP of 4, accounting for efficiency gains from waste heat integration, the corresponding electrical input capacity is around 134 kW, leading to an annual electricity consumption of approximately 390,390 kWh/year. A conservative assumption of a 15-year lifespan for the heat pump was adopted, requiring at least one full equipment replacement within the project's 25-year timeframe (Arpagaus et al., 2023). The CAPEX for high-temperature heat pumps varies depending on factors such as compressor type, working fluid (refrigerant), maximum heating capacity, and target supply temperature. Reported literature values range widely, from several hundred to over a thousand USD per kW of process heat output (USD/kW_{th}) (Akar et al., 2021; Arpagaus et al., 2023; Marina et al., 2021). An average of approximately 650 USD/kW_{th} (Marina et al., 2021) was adopted to conservatively account for additional import and integration costs, totalling around 347,608 USD/unit. While O&M costs can be categorised into fixed and variable components, total annual O&M expenses of approximately 3% of CAPEX were considered, based on established guidelines (Arpagaus & Bertsch, 2019). This equates to an estimated 10,428 USD/year, encompassing routine inspections, preventive maintenance, refrigerant management, and periodic compressor overhauls to ensure sustained operational efficiency and reliability.

The electricity demand for both existing processes (108,489 kWh/year) and the new heat pump load (390,390 kWh/year) is fully covered by renewable energy sources. This scenario was modelled in HOMER Pro software using solar PV systems coupled with battery storage, ensuring a fully renewable and reliable energy supply without diesel or grid backup. Scenario 3A, featuring lead-acid batteries, requires adding a 1,200 kW_p solar PV system, 2,300 kWh battery capacity, and upgrading the inverter capacity to 200 kW. Scenario 3B, using lithium-ion batteries, requires an additional 1,300 kW_p solar PV capacity and 1,150 kWh battery storage. Scenario 3A and 3B are each coupled with their respective cereal milling facility setups (2A and 2B). However, as cereal milling remains unchanged from previous scenarios, it is not further analysed here. The complete technical setup, including sub-scenarios 3A and 3B, is presented in Figure 40.

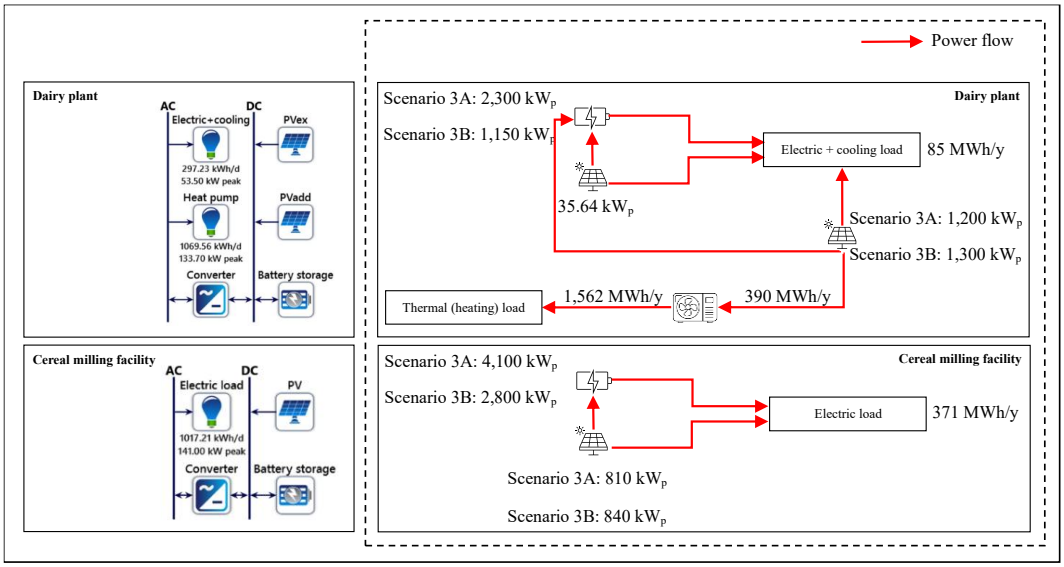

Figure 40. Case study 3: Technical setup of scenario 3

Notes: The left graphic was modelled with HOMER Pro, and the right graphic was modelled by the author. Scenario 3A contains lead-acid battery storage, while scenario 3B contains lithium-ion battery storage.

Abbreviations: kW = kilowatt; kWh/d = kilowatt-hour per day; kWh/y = kilowatt-hour per year; kW_p = kilowatt peak; MWh/y = megawatt-hour per year; PV = photovoltaic; PV_{add} = additional photovoltaic system; PV_{ex} = existing photovoltaic system

Similar to scenario 2, scenario 3 achieves full reliance on renewable energy. The cereal milling farm maintains its renewable energy setup, where milling activities are powered by solar PV with battery storage, identical to scenario 2. However, scenario 3 advances further by electrifying the thermal demand at the dairy plant, transitioning entirely to solar PV with battery storage. In previous cases, including the base scenario and scenarios 1 and 2, only electric equipment and cooling systems were powered by electricity. With this transition, the entire energy demand of the dairy plant is now met exclusively by solar PV and battery storage, achieving a 100% renewable setup. The analysis continues to focus on the dairy plant since the cereal milling configuration remains equivalent to scenario 2, where scenario 2A corresponds to 3A and scenario 2B to 3B. This results in scenario 3A employing lead-acid batteries at both locations, while scenario 3B integrates lithium-ion batteries at both sites.

The solar PV and battery storage systems effectively meet the dairy plant's energy demand, with unmet demand kept below 0.1% of total annual energy consumption. This amounts to less than 500 kWh/year for both sub-scenarios,

ensuring near-complete electrification. In scenario 3A, the lead-acid battery system supplies 6% of the dairy plant's electricity needs, storing and discharging 26,952 kWh/year, whereas in scenario 3B, the lithium-ion system accounts for 5%, delivering 24,938 kWh/year. The lead-acid system in scenario 3A provides approximately 24 hours of autonomy at the dairy plant, while the lithium-ion setup in scenario 3B offers 16 hours, allowing for extended operation without solar input. While one might consider replacing battery storage at the dairy plant with a diesel generator as a backup solution, this would significantly increase fossil fuel consumption. The base case scenario required only 4,308 kWh/year of diesel, meaning that shifting to diesel in scenario 3 would necessitate a fivefold increase in diesel consumption. However, the enhancement scenarios primarily aim to minimise fossil fuel reliance and avoid diesel-based backup solutions.

As observed in scenario 2, the installed PV capacity ensures system reliability and resilience but also results in significant curtailment due to surplus energy that cannot be effectively stored or utilised. Scenario 3 exhibits a similar ratio of excess electricity compared to total generation as scenario 2. Specifically, in scenario 3A, excess energy at the dairy facility reaches 73%, exceeding 1,400 MWh/year. In scenario 3B, where lithium-ion batteries are utilised, excess electricity is even higher, reaching 75% (over 1,600 MWh/year). Despite the additional electrified load, this increase was insufficient to significantly reduce surplus electricity. Instead, it led to an expanded PV and battery capacity, maintaining the same excess electricity ratio. This is primarily due to system optimisation in HOMER Pro, which sought the lowest NPC while ensuring complete demand coverage, resulting in an oversized PV system.

From an economic perspective, scenario 3B achieves a 20% lower NPC than scenario 3A while reducing operating costs by 63%, highlighting the trade-off between smaller battery capacity and the long-term operational savings of lithium-ion batteries. The initial capital costs for both sub-scenarios are nearly identical, with scenario 3B incurring slightly above 1% lower upfront costs than scenario 3A. Scenario 3B benefits from significantly reduced operating costs over the project's lifetime. Compared to the base case, NPC increases by 230% in scenario 3A and 163% in scenario 3B. Operating costs remain nearly unchanged from the base case in scenario 3A (a marginal 1% increase) but decline significantly by 63% in scenario 3B. Despite the high initial investment, both sub-scenarios eliminate expenses related to grid electricity, diesel fuel, and diesel O&M, with scenario 3B particularly benefiting from lower long-term maintenance costs. In both configurations, solar PV CAPEX constitutes the largest cost component,

accounting for 54% and 72% of NPC in scenarios 3A and 3B, respectively. In scenario 3A, battery replacement costs represent the second-largest expense (21%), followed by lead-acid battery CAPEX (11%) and battery O&M (9%). Conversely, the second-largest cost component of sub-scenario 3B is lithium-ion battery CAPEX, amounting to 9% of NPC, with O&M and replacement costs each contributing approximately 7%. Initial investment costs, O&M, and replacement costs for the heat pump contribute a minor 4-5% and 1-2% of NPC, respectively, in both sub-scenarios. Salvage values from key equipment, including boilers, diesel generators, and lithium-ion batteries in scenario 3B, provide modest cost reductions. These salvage values account for 6% of NPC in scenario 3A and 8% in scenario 3B, mirroring the total cost offsets observed in scenario 2.

From an environmental perspective, scenario 3 remains entirely emissions-free, as both facilities operate exclusively on solar PV coupled with battery storage. The complete elimination of grid electricity and diesel backup ensures that scope 1 and scope 2 emissions are reduced to zero, demonstrating the feasibility of a fully renewable, off-grid energy system for both facilities.

Scenario 4: Solar PV with battery storage and biogas production and utilisation at the dairy plant for thermal (heating) demand

Scenario 4 introduces an additional improvement to the dairy plant while keeping the cereal milling facility configuration exactly as introduced first in scenario 2 and then adopted in scenario 3. As in these previous scenarios, two battery storage options are considered: scenario 4A with lead-acid batteries and scenario 4B with lithium-ion batteries, matching the setup of scenarios 2A and 2B (and 3A and 3B), respectively. Given that the cereal milling facility remains unchanged, the discussion here will specifically highlight enhancements at the dairy plant, although both facilities are integrated into the economic and technical analyses.

In scenario 4, the dairy plant's electrical needs continue to be fully covered by a combination of solar PV systems and battery storage, without any dependence on grid power or diesel generators. However, this scenario uniquely addresses the plant's thermal (heating) demand by replacing the existing biomass briquette boiler with a new biogas boiler system. This system generates biogas through AD of cow manure. Before combustion, the biogas undergoes minimal purification to remove major impurities such as hydrogen sulphide and moisture, making it suitable for boiler use (Ahmed et al., 2021; Allegue & Hinge, 2014; Bauer et al., 2013).

Currently, there is no formal manure treatment system at the dairy facility; manure is instead channelled directly onto agricultural fields via underground pipes. Implementing AD would utilise manure more efficiently by producing renewable energy and digestate, a nutrient-rich organic fertiliser (Chojnacka & Moustakas, 2024; Haraldsen et al., 2011; Koszel & Lorencowicz, 2015). This approach not only helps reduce environmental impacts but could also lower reliance on chemical fertilisers. While digestate provides a valuable secondary benefit, the primary economic evaluation here focuses on energy production.

Biogas production is well-established in Kenya, dating back to small-scale projects initiated in the mid-1950s (Laichena & Wafula, 2002). Over the years, diverse digester designs such as Indian and Chinese types have been adopted. By 1986, approximately 200 digesters had been installed, with further expansions driven by targeted government initiatives and programs such as the African Biogas Partnership Programme (Laichena & Wafula, 2002; Mailu et al., 2019). Between 2009 and 2013, phase I of this programme facilitated the installation of over 9,800 biogas plants, followed by an additional 3,400 plants during phase II (2014-2017) (Mailu et al., 2019). Despite early challenges, these sustained efforts have significantly promoted biogas technology, contributing to rural employment, improved health outcomes, reduced deforestation, and lower GHG emissions. Given this established history and continuing support, biogas emerges as a viable and promising option for meeting the dairy plant's heating needs, warranting a detailed technical and economic assessment.

To meet the dairy plant's annual heating requirement of approximately 1,561,560 kWh, the necessary biogas production was calculated. Employing a biogas LHV of 22 MJ/m^3 (Cappannelli et al., 2020) and a density of 1.15 MJ/kg (Jørgensen, 2009), the heating content translates to roughly 6.11 kWh/m^3. A boiler efficiency of 80% was assumed, which is a conservative yet realistic figure reflecting typical operational conditions without advanced heat recovery measures such as economisers. While modern gaseous boilers commonly achieve efficiencies between 85-95% (Al-Mtury et al., 2024), the selection of 80% provides a pragmatic and achievable baseline. This still represents a substantial improvement over the existing biomass boiler's 65% efficiency. Under these assumptions, the annual biogas requirement is approximately 319,410 m^3/year, corresponding to a daily requirement of around 875 m^3/day.

Given the notable regional differences in cow sizes and manure yields, the analysis specifically considered data relevant to the East African context. Typical

cow weights in East Africa are around 150 kg (Machila et al., 2008), significantly lower than an estimate of 630 kg/cow from an U.S. American study (Nennich et al., 2005). Consequently, assuming a clear linear relationship between cow weight and manure excretion (Nennich et al., 2005), manure production was estimated at about 16 kg/cow-day. Initial preliminary calculations, using a basic biogas yield of 0.036 m^3 per kg of fresh manure, indicated a biogas yield of around 0.57 m^3/cow-day. However, employing a more scientifically robust approach based on volatile solids (VS), with a biogas yield of 380 L per kg VS (L/kg VS), 10% total solids (TS), and 80% VS, resulted in a more conservative biogas yield estimate of about 0.48 m^3 /cow-day. To meet the daily biogas requirement, a herd size of roughly 1,819 cows, producing approximately 28.8 tonnes of manure daily, is needed. With the existing 100 cows providing only about 7% of the required manure, significant herd expansion or co-digestion with other organic materials would be necessary. However, for the sake of simplicity, this scenario explicitly focuses on cow manure alone, assuming the necessary increase in herd size is achieved either directly by the dairy entrepreneur or through manure collection from nearby farms at no additional cost.

This substantial manure input requires considerable anaerobic digestion infrastructure, estimated at around 1,008 m^3 digester volume, reflecting a hydraulic retention time towards the higher end of the commonly used range of 10-40 days to ensure ample operational storage and flexibility (Bhave & Patil, 2022; Elango et al., 2007). Various AD technologies exist, each suitable for specific operational scales and requirements (Sasse, 1988). Fixed-dome digesters offer durability exceeding 20 years with minimal maintenance, making them ideal for steady, long-term operation. Floating-drum digesters provide consistent gas pressure but require frequent maintenance due to corrosion risks and have an approximate lifespan of 15 years. Tubular plastic digesters are cost-effective and easily installed but typically last only 5 to 10 years. Although this study does not commit to a specific digester type, the investment calculations assume that the AD will not require replacement over the project lifespan. This assumption reflects the durability associated with long-lasting systems such as fixed-dome designs, which are common in the region and noted for their low maintenance and extended operational life (Laichena & Wafula, 2002; Mailu et al., 2019; Sasse, 1988). Having said this, average regional installation and commissioning costs guided the CAPEX estimates. Baseline costs for the AD including installation were initially estimated at approximately 144 USD per m^3 of digester capacity, derived from regional market data indicating an installation cost of 480,000 KES for a 24 m^3 capacity digester (Kenpro, 2024). For context, household-scale digesters in Kenya typically

cost around 90 USD per m^3 capacity (Opinya & Kimuge, 2020; Sebola & Tesfasgiorgis, 2015). To establish a comprehensive total CAPEX estimate in which the installation of the AD accounts for 50%, additional project components were integrated, guided by industry benchmarks and studies. Structural and civil works accounted for approximately 10% of the total cost, while piping and valves comprised about 5%, drawing on cost distributions from a detailed South African biogas system study (Sebola & Tesfasgiorgis, 2015). Gas cleaning system costs, essential for removing impurities such as hydrogen sulphide, were estimated at 10% of CAPEX, aligning with standard industry practice (Choudhury et al., 2019). Boiler integration costs were assumed to represent around 15% of total expenditure, reflecting typical project breakdowns (Mezzadri & Francescato, 2014). For consistency with previous system configurations using briquette-fuelled boilers, the biogas boiler is also assumed to have a service life of 20 years (IRENA Secretariat, 2012). Lastly, a contingency allowance of 10% was included to cover unforeseen expenditures. These combined elements yielded an adjusted and comprehensive CAPEX of roughly 287 USD per m^3/AD capacity, culminating in a total estimated investment of approximately 290,000 USD. This overall estimate aligns closely with other documented projects, despite variations in geographical location, cow size, manure volume, and digester scale. For example, for an AD system treating around 12 tonnes of cow manure daily, Mezzadri & Francescato, 2014) reported a CAPEX of around 276,600 EUR, which included a combined heat and power (CHP) unit and accounted for relatively higher labour costs, excluding 40% of the CAPEX that was subsidised. Similarly, Sebola & Tesfasgiorgis (2015) indicated a total CAPEX of approximately 221,000 USD treating 2 tonnes of cow manure daily. Annual O&M expenses were conservatively estimated at around 6% of total CAPEX, encompassing both fixed and variable cost components (Mezzadri & Francescato, 2014).

Once biogas is produced, it undergoes a purification process primarily aimed at removing hydrogen sulphide and moisture. This purification step increases electrical energy consumption by about 2% compared to previous enhancement scenarios. The estimated electrical demand is based on literature values, which calculate an energy usage of approximately 0.0053 kWh per cubic meter of biogas entering the cleaning unit, derived from an established scientific baseline of 9000 kWh per year (operating 8,500 hours per year) at a flow rate of 200 m^3/h (Allegue & Hinge, 2014). For the dairy plant's calculated daily biogas requirement of 875 m^3/day, corresponding to a flow rate of about 110 m^3/h over an assumed 8-hour operational period, this results in an additional electrical consumption of

approximately 4.6 kWh/day. It is further assumed that biogas purification occurs under ideal conditions, with no volumetric losses during the cleaning process.

For the dairy plant's electrical requirements, two sub-scenarios (4A and 4B) were modelled, distinguished by the type of battery storage, lead-acid batteries for scenario 4A, and lithium-ion batteries for scenario 4B. Using HOMER Pro, scenario 4A requires an inverter capacity of 75 kW, additional solar PV capacity of 200 kW_p, and 700 kWh of lead-acid battery storage. Scenario 4B involves a slightly larger solar PV system of 250 kW_p combined with a more efficient 280 kWh lithium-ion battery system. The full technical configuration for both the dairy and cereal milling plants is comprehensively detailed in Figure 41.

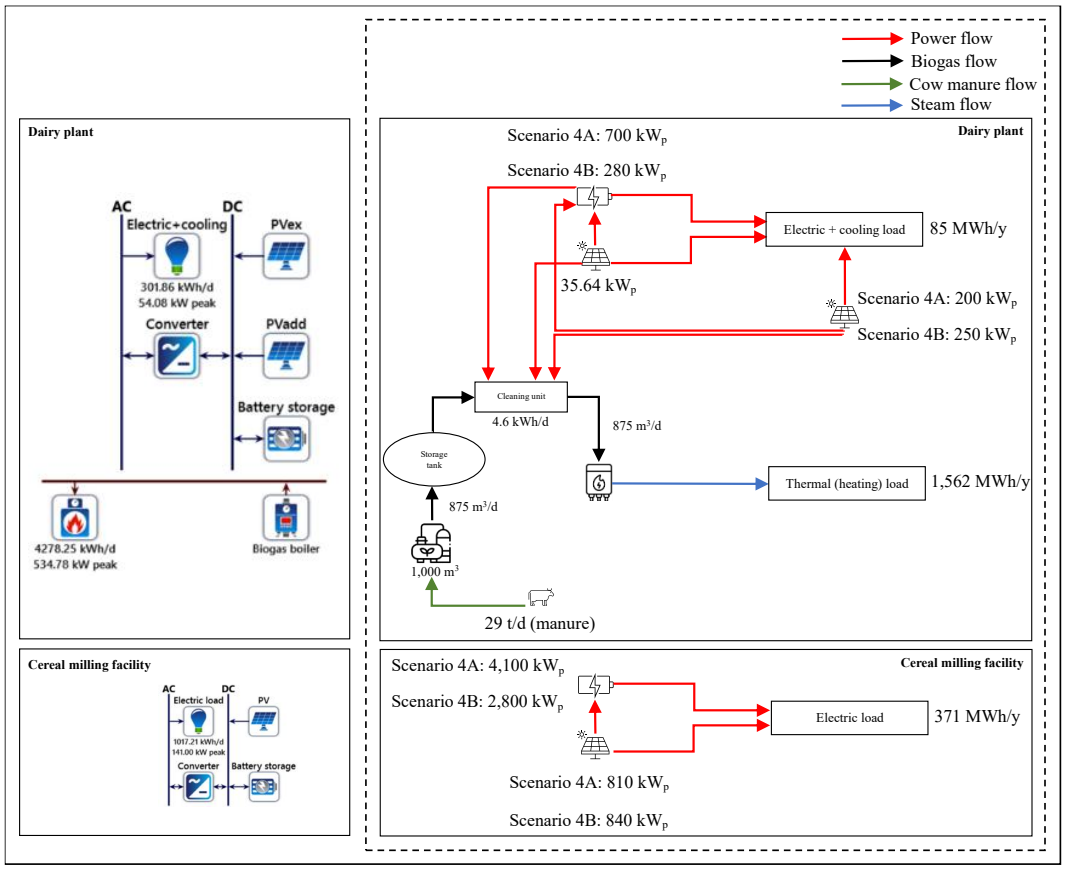

Figure 41. Case study 3: Technical setup of scenario 4

Notes: The left graphic was modelled with HOMER Pro, and the right graphic was modelled by the author. Scenario 4A contains lead-acid battery storage, while scenario 4B contains lithium-ion battery storage.

Abbreviations: kW = kilowatt; kWh/d = kilowatt-hour per day; kWh/y = kilowatt-hour per year; kW_p = kilowatt peak; MWh/y = megawatt-hour per year; PV = photovoltaic; PV_{add} = additional photovoltaic system; PV_{ex} = existing photovoltaic system; t/d = tonnes per day

Similar to previous scenarios, scenario 4 achieves complete reliance on renewable energy, though it introduces distinctive refinements, particularly at the dairy plant. The cereal milling facility remains fully powered by solar PV systems with battery storage, identical to scenarios 2 and 3, ensuring consistency in renewable energy usage. However, at the dairy plant, scenario 4 introduces an additional consideration due to the biogas cleaning process, resulting in a modest 2% increase in electricity consumption. This scenario uniquely integrates a biogas boiler, which uses biogas produced via AD from cow manure generated onsite, effectively replacing biomass briquettes previously used for heating. Thus, the dairy plant is fully supported by solar PV with battery storage for electrical and cooling demands, and by biogas for heating.

In terms of electrical infrastructure, scenario 4 closely mirrors scenario 2, differing slightly in battery storage requirements, both sub-scenarios 4A (lead-acid) and 4B (lithium-ion) necessitate an additional 20 kWh of battery capacity compared to their scenario 2 counterparts. Specifically, scenario 4A employs a solar PV capacity of 200 kW_p paired with 700 kWh lead-acid battery storage, while scenario 4B uses a larger solar PV array of 250 kW_p coupled with 680 kWh lithium-ion batteries. This adjustment leads to a minimal yet noteworthy reduction in curtailed energy by approximately one percentage point in each sub-scenario, resulting in curtailment levels of 68% and 74% for scenarios 4A and 4B respectively. Performance-wise, these modest adjustments do not significantly alter the outcomes observed in scenario 2. Solar PV systems effectively meet the energy demands at the dairy plant, consistently maintaining unmet electricity demand below 0.1% annually. Like scenario 2, lead-acid battery storage in scenario 4A contributes notably, covering around 14% of the dairy plant's total electricity needs, storing and delivering 15,587 kWh/year. At the cereal milling facility, the system provides approximately 11% of the annual electrical demand (39,071 kWh/year). The autonomy provided by lead-acid storage remains robust, approximately 33 hours for the dairy plant and 58 hours for the cereal facility, signifying extended operational resilience even during extended periods without solar input. In contrast, the lithium-ion batteries in scenario 4B, while smaller in capacity, still contribute effectively, meeting approximately 13% (14,313 kWh/year) of the dairy plant's demand and around 10% (37,743 kWh/year) at the cereal milling site. This reduction in storage capacity marginally impacts autonomy, offering around 18

hours at the dairy plant (slightly improved by one hour compared to scenario 2) and approximately 53 hours at the cereal milling facility.

Economically, scenario 4B provides substantial benefits, achieving a 24% lower NPC compared to scenario 4A and significantly reducing operating expenses by 68%. These financial advantages underscore the long-term value of investing in lithium-ion technology, despite its higher upfront costs. Initial CAPEX between sub-scenarios 4A and 4B remain closely aligned, with scenario 4B marginally, by 2%, less expensive. When benchmarked against the base case, scenario 4A experiences a 112% rise in NPC, while scenario 4B sees a more modest 62% increase. Notably, operational costs decrease substantially, by 30% in scenario 4A and notably by 77% in scenario 4B. Both configurations eliminate costs associated with grid electricity, diesel fuel, and associated maintenance. Scenario 4B particularly benefits from reduced long-term battery maintenance and replacement expenses. A breakdown of cost components reveals that solar PV CAPEX remains the largest cost factor, representing 48% and 67% of total NPC for scenarios 4A and 4B, respectively. In scenario 4A, battery replacement costs are the second largest expenditure at 24%, followed by the initial lead-acid battery investment (13%) and battery O&M (11%). In scenario 4B, lithium-ion battery CAPEX comprises 11% of NPC, with O&M, and replacement costs each accounting for approximately 9%. Meanwhile, CAPEX for the biogas system (including AD, cleaning unit, and new boiler) contributes 6% in scenario 4A and 7% in scenario 4B, with additional O&M expenses adding around 4-5% across both sub-scenarios. Salvage values, particularly from significant equipment such as boilers, diesel generators, and lithium-ion batteries in scenario 4B, offer modest but meaningful cost reductions, accounting for about 9% of NPC in scenario 4A and 12% in scenario 4B.

From an environmental perspective, scenario 4 is fully emissions-free, underscored by the transition to biogas and the complete reliance on solar energy with battery storage. Utilising cow manure in the biogas digester further enhances sustainability by converting waste into a valuable energy resource, thereby eliminating emissions associated with unmanaged manure disposal. This comprehensive shift ensures zero scope 1 and scope 2 emissions, validating the feasibility and practicality of fully renewable, off-grid energy solutions at both the dairy and cereal milling facilities.

Scenario analysis summary

The economic and environmental comparison of the enhancement scenarios highlights the diverse benefits and trade-offs involved in transitioning toward renewable energy solutions. Scenario 1 introduces a relatively modest intervention through solar PV and net metering, requiring limited upfront investment and achieving a meaningful reduction in both operating costs and emissions. From scenario 2 onwards, all configurations fully eliminate GHG emissions, making them strong candidates from an environmental perspective. However, this comes with varying economic implications. Scenario 2 marks a major shift by eliminating grid and diesel dependency entirely through solar PV and battery storage, yet it also results in higher investment and NPC. Scenario 3 involves a full electrification of the dairy plant, replacing the briquette boiler with a high-temperature heat pump, resulting in the highest recorded initial investment costs and NPC, though the lithium-ion battery option is more cost-effective compared to its lead-acid counterpart. Scenario 4 offers a particularly compelling alternative. Despite incorporating an AD system and a biogas boiler for thermal needs, it delivers the lowest operating costs across all scenarios and total investment costs that are comparable to, or even lower than, those in scenario 2. Table 24 summarises the main economic and environmental indicators under assessment.

Table 24. Case study 3: Comparison of initial investment, NPC, annual operating costs and GHG emissions between base case and scenarios 1-4

	Initial investment	**NPC**	**Operating costs**	**GHG emissions**
Unit	USD	USD	USD/year	$tCO_{2\text{-}eq}$/year
Base case	0	2,464,800	209,600	133.92
Scenario 1	527,400	2,528,200	170,200	73.75
Scenario 2A	3,186,100	6,675,100	296,700	0.00
Scenario 2B	4,073,800	7,060,800	254,000	0.00
Scenario 3A	5,641,100	8,132,400	211,900	0.00

Scenario 3B	5,559,800	6,470,200	77,400	0.00
Scenario 4A	3,515,500	5,233,000	146,100	0.00
Scenario 4B	3,444,100	3,999,100	47,200	0.00

Notes: All cost figures in USD are rounded to the nearest hundred to enhance readability and facilitate comparison.

Abbreviations: $tCO_{2\text{-}eq}$ = tonne of carbon dioxide equivalent; GHG = greenhouse gas; NPC = net present cost; USD = United States dollar

Each scenario provides specific advantages depending on the priorities and resources of the implementing stakeholder. While some options prioritise minimal investment with moderate improvements, others require greater upfront capital but offer deeper long-term savings and environmental benefits. The choice between them depends not only on available financing but also on broader goals, such as reducing emissions, improving energy independence, or maximising economic efficiency.

7.3.3.3 MTF evaluation

Based on the World Bank's MTF, this chapter evaluates the four enhancement scenarios for case study 3.

Several assumptions underpin the MTF evaluation. The capacity attribute initially fulfilled tier 5 requirements in the base case. Notably, even with a substantial 27% increase in electrical demand at the dairy plant compared to the base scenario, all enhancement scenarios maintain full satisfaction of both electrical and non-electrical requirements, particularly regarding availability and reliability. For non-electrical energy carriers, it is assumed that biomass briquettes and biogas consistently meet thermal requirements with uninterrupted availability and reliability. Electric energy supply via solar PV systems is specifically quantified; scenario 1 maintains uninterrupted supply due to net metering integration, while scenarios 2 through 4 encounter minimal availability limitations of approximately 0.1% unmet load. This translates to roughly 1-2 minutes of outages per week at both facilities under scenario 2 and up to 10 minutes weekly at the dairy plant for scenarios 3 and 4. All scenarios also achieve tier 5 affordability standards. Scenario 1 notably reduces grid electricity expenses through net metering, whereas scenarios 2 through 4 assume electric (solar PV) and non-electric (biogas in scenario 4)

energy supply costs at or below existing grid tariffs. Biomass briquette costs in scenarios 1 and 2 remain significantly lower than grid tariffs, reinforcing affordability. Convenience assumptions indicate negligible impacts from sourcing biomass briquettes or biogas production on productive activities. Health ratings position biomass briquettes at tier 3 due to controlled emissions, while scenarios 3 and 4 elevate this to tier 5 through the use of cleaner energy sources, specifically electrification and biogas. Safety attributes are assumed unchanged from the base scenario across all scenarios.

Figure 42 presents the tier performance evolution from the base case through scenarios 1-4 for the Kenyan case study, using the World Bank's MTF. Initially, the base case achieves an overall tier 3 performance, primarily limited by health implications from biomass briquette use. Scenarios 1 and 2 maintain this overall tier 3 score due to ongoing reliance on biomass briquettes, with the health attribute continuing as the lowest-performing factor. However, both scenarios significantly enhance electric supply performance to tier 5, driven by improved availability and reliability through solar PV integration. Scenario 1 benefits from net metering arrangements, and scenario 2 further advances through solar PV and battery storage. Remarkably, scenarios 3 and 4 achieve an overall maximum tier 5 performance. Scenario 3 accomplishes this through complete electrification of both electric and thermal energy demands, while scenario 4 introduces biogas for thermal energy. These two scenarios highlight how integrated renewable energy technologies markedly advance overall energy access performance.

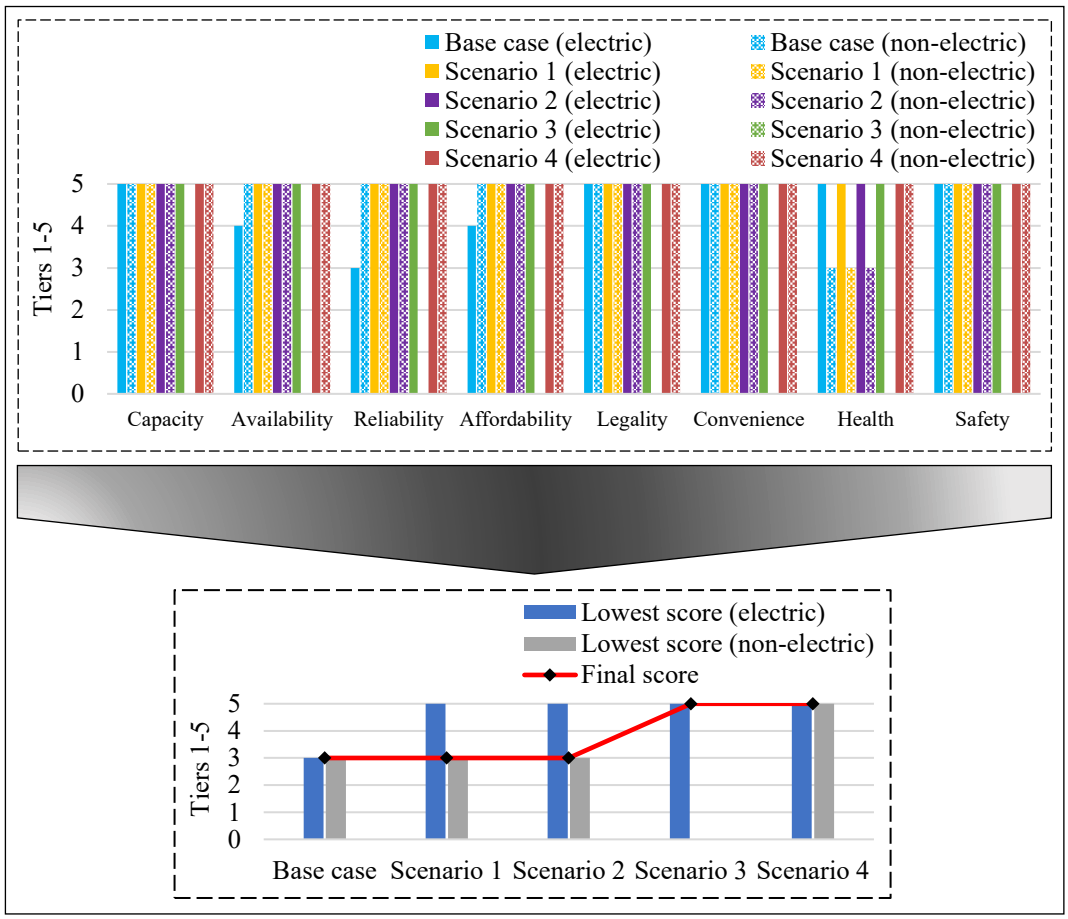

Figure 42. Case study 3: MTF tier performance comparison between base case and scenarios 1-4

Notes: Scenario 3 is fully electrified; therefore, the absence of an assessment for non-electric energy sources does not indicate a tier 0 rating but reflects that non-electric sources are not applicable in this scenario.

The analysis underscores the transformative potential of targeted energy enhancements, particularly full electrification and biogas integration, in improving operational sustainability, environmental health, and overall convenience. Transitioning from conventional biomass briquettes to cleaner energy solutions such as biogas or full electrification significantly elevates energy access performance.

7.3.4 Case study 4: Malawi – Maize milling

Located in Mguwata, in Malawi's Lilongwe district, this micro-sized enterprise has a female-male co-ownership structure and is run by a married couple. The

business is unregistered and operates entirely off-grid, relying on two diesel generators, one used for ground maize, and the other for maize flour, producing approximately 54 tonnes of processed maize per month with a profit margin of around 42%. Maize milling is the primary activity, serving the entire village as off-takers. The energy expenditure accounts for the business's entire operating costs, covering fuel, maintenance, and repairs. The enterprise generates 500 kg of maize husks daily, which is not considered waste. Instead, it is used as feed for goats and other livestock raised by the owners and, during the dry season, even consumed by villagers.

The female co-owner highlights several operational challenges, including the physical effort required for manual parts of the grinder and mill, logistical difficulties with maintenance and repairs requiring trips to the nearest town, and the lack of a protective shed for one of the maize mills, making it difficult to operate during rain. Gender-specific challenges include balancing work responsibilities with domestic obligations.

The female co-owner is unfamiliar with renewable energy technologies and therefore lacks a direct motivation to adopt new systems. Therefore, the main barrier to implementation includes limited knowledge, combined with the need for compatible equipment to perform maize milling. However, she expresses a willingness to invest in renewable energy solutions if they address the challenges posed by the diesel generators, with an openness to taking a loan and repaying around 250 USD/month.

Applying the World Bank's MTF, the enterprise achieves an overall energy access score of 3. Challenges include high diesel costs compared to grid tariffs, difficulties stemming from the off-grid location, transportation issues for diesel, and health impacts from generator fumes and noise pollution. While fuel shortages average approximately 1.3 hours per week, it is noteworthy that for three months during the year of the interview, fuel availability in the country was entirely depleted (Gad & Leone, 2025). These findings align with literature and press releases from the Malawi Energy Regulatory Authority (MERA) highlighting persistent fuel crises in Malawi, which have severely impacted economic stability and daily operations for decades (Engel et al., 2025; Kampanje, 2012; Mhone, 2024, 2025). The World Bank attributes these shortages to foreign exchange constraints, deferred price corrections, implicit subsidies, and logistical challenges, all of which have led to recurrent supply disruptions (Engel et al., 2025). Regulated pump prices, set too low to cover escalating import and transport costs, have exacerbated cash

constraints, further straining fuel availability (Engel et al., 2025; Kampanje, 2012). MERA has acknowledged these issues, citing fuel service station malpractices as an additional factor contributing to supply disruptions (Mhone, 2025). Despite periodic government assurances that fuel reserves are sufficient (Mhone, 2024), the recurrence of prolonged shortages underscores the country's vulnerability and the urgent need for sustainable energy solutions to enhance energy security and economic resilience.

This background lays the groundwork for a comprehensive baseline assessment, detailing the enterprise's current energy access conditions, technical system setup, and environmental performance. Together, these elements provide a critical reference point for evaluating the relevance and impact of proposed energy improvement scenarios.

7.3.4.1 Base case

Case study 4 relies on two diesel generators to power a maize flour mill and a maize grinder, which typically operate in parallel from 6:00 to 18:00, five days a week. Under normal conditions, this results in 12 hours of daily operation and a monthly diesel consumption of approximately 1,500 litres, equivalent to an energy expenditure of around 1,769 USD/month. Although operational disruptions such as fuel shortages and intermittent idle periods are acknowledged, these are treated as temporary disruptions that are not reflective of standard operations. For modelling purposes, the base case reflects optimised operational conditions, assuming consistent production without fuel-related disruptions. This approach aligns with the enterprise's intended output and energy requirements under stable supply scenarios. Table 25 summarises the key productive use applications for case study 4.

Table 25. Case study 4: Summary of productive use applications

Process	**Temperature**	**Energy carrier**	**Appliance**		**Power rating or consumption**	
	°C	Type	Count	Type	Value	Unit
Milling	-	Diesel-based	1	Maize flour mill	750	L/month

		mechanical energy				
Grinding	-	Diesel-based mechanical energy	1	Maize grinder	750	L/month

Abbreviations: °C = degree Celsius; L = litre

The capacities of the diesel generators were estimated because nameplate information was unavailable, and the owners could not provide exact specifications. The estimation process integrated daily diesel consumption data, production rates, typical generator efficiencies, and a comparison with similar appliances from the same brand, alongside general characteristics of small milling machines commonly used in Africa. The initial estimates were derived using a supply-side approach, as fuel consumption was the only directly available data. The supply-side model was then refined using HOMER Pro to validate and adjust the assumptions.

The theoretical generator capacities were calculated from the energy content of the diesel fuel, using its LHV (43 MJ/kg) and density (0.84 kg/L) (Garg et al., 2006; Statistic Netherlands, 2025). An average nominal efficiency of 30% for diesel generators operating at full load was assumed but reduced to 20% to account for the relatively old generators, their likely suboptimal operation, and partial load conditions (Stiel & Skyllas-Kazacos, 2012). Daily operation of 12 hours/day was assumed, with the generator for the grinder estimated to be 1.5 times the capacity of the generator for the mill, based on observations of their relative outputs. These estimates were mathematically calculated, yielding values of 4.68 kW for the maize mill and 7.02 kW for the maize grinder, which were then rounded to 5 kW and 7 kW, respectively.

To achieve a more accurate performance profile, HOMER Pro was used to model the system. An annual fuel consumption target of 18,200 L/year was set, and the fuel consumption curve was calibrated within the typical operational range of diesel generators, accounting for both load-dependent consumption and idle mode operation (Decker et al., 2016). The generator-to-mill efficiency, representing the proportion of electrical output from the generator effectively utilised by the milling machinery, was set to 75%. While higher-performing diesel-powered maize mills achieve an efficiency of 89% from generator to mill (Agason Motors, 2025). This efficiency was conservatively reduced, resulting in calculated capacities of 3.51 kW

for the mill and 5.27 kW for the grinder, rounded to 3.5 kW and 5 kW, respectively. Similarly, the minimum load ratio was set at approximately 75%. This assumption ensures that the generator produces only the power required to meet the exact demand of the maize mill and grinder, avoiding any excess generation. By aligning the generator's efficiency with its minimum load ratio, the model reflects an optimised scenario where the generator's output is precisely matched to the milling power needs.

For further validation, the demand-side calculation was cross-checked using production data. Literature suggests that 1 kW of power processes 25-30 kg/h, with a conservative value of 25 kg/h applied (Clarke & Rottger, 2006). The production rates of 1,000 kg/12h for the mill and 1,500 kg/12h for the grinder correspond to processing rates of 83 kg/h and 125 kg/h, respectively. These require 3.3 kW for the mill and 5 kW for the grinder. These values are consistent with the supply-side estimates, affirming the validity of the assumptions.

The model results indicate a total annual energy demand of 27,393 kWh/year to meet the needs of the mill and grinder. The average diesel consumption of 2.08 L/h, compared to a value of 3 L/h that can be found in literature (Clarke & Rottger, 2006) is justified as the literature value represents an average across varying contexts, whereas the fuel curve in this study was specifically adjusted to reflect the consumption profile of the case study. Furthermore, the system's mean electrical efficiency of approximately 15% aligns with expectations for ageing, off-grid diesel generators operating under partial load conditions, further supporting the plausibility of the adjusted fuel consumption value. The final technical setup of the base case is presented in Figure 43.

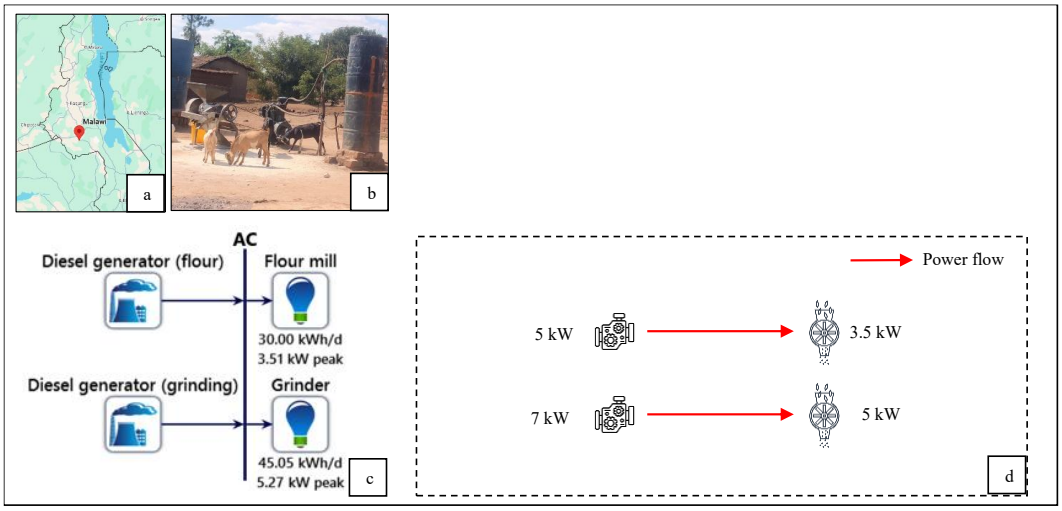

Figure 43. Case study 4: Technical setup of the base case

Notes: a) Geographic location, source: google.maps; b) Diesel generator and maize grinder, source: author (used with permission from the entrepreneur and author holds rights to use and publish); (c) Technical setup designed with HOMER Pro, including calculated values; d) Technical setup designed by the author, including rounded values.

Abbreviations: kW = kilowatt; kWh/d = kilowatt-hour per day

The economic analysis of the Malawian case study highlights the significant expenses associated with the two diesel generators. Each generator consumes 35 litres of fuel per weekday at a cost of approximately 1.26 USD/L, resulting in an annual fuel expenditure of 22,990 USD. Additional costs include fuel transportation and generator maintenance, which, according to the entrepreneur, are considerable but not precisely tracked due to a lack of bookkeeping. Based on HOMER Pro's default assumptions but increased by a third to account for additional expenditure due to the enterprise's remote location, these costs are estimated at 0.04 USD per operating hour per kW. With an estimated 3,120 operating hours per year (12 hours per weekday for 52 weeks), maintenance expenses are projected at 1,460 USD/year for both generators. This figure, representing approximately 6% of the annual fuel costs, appears reasonable, especially given the village's location and need to travel around 70 km to the nearest town where fuel and repair services would be procured.

Generator replacement costs are estimated at 600 USD/kW, amounting to 7,020 USD every 6-7 years (assuming a 20,000-hour operating lifetime).

For this case study, a 9% nominal discount rate was applied, consistent with rates typically used for renewable energy projects in the country (Borgstein et al., 2019), ensuring consistency in evaluating both the diesel-based base case and

renewable energy scenarios under identical financial conditions and reflecting the local cost of capital and market norms. Over a 25-year project horizon with a 9% discount rate, the NPC and operating costs reveal that fuel accounts for the majority (91%) of total costs, followed by O&M (6%), which includes fuel transportation and repairs. Replacement costs contribute less than 3% of the total NPC, while the salvage value at the project's end is negligible. The cost breakdown is summarised in Table 26.

Table 26. Case study 4: Net present cost and operating costs of the base case

Component	NPC (USD)	Operating costs (USD/year)	Share of NPC (%)
Diesel generators			
O&M (maintenance, transport)	14,343	1,460	6%
Fuel consumption	225,824	22,990	91%
Replacement	7,383	752	3%
Total salvage value	-81	-8	< -1%
Total	**247,468**	**25,194**	**100%**

Notes: A nominal discount rate of 9% is applied and the project lifetime is set for 25 years. Due to rounding, the sum of individual items may not exactly match the total. The total value, however, reflects a more accurate value.

Abbreviations: % = percent; NPC = net present cost; O&M = operation and maintenance; USD = United States dollar

This analysis not only underscores the significant financial burden of relying on diesel generators but also sets the stage to examine their substantial environmental impact, which further emphasises the need for sustainable energy alternatives.

The environmental impact of the Malawian case study is evaluated by quantifying direct and indirect GHG emissions under scope 1 and scope 3,

respectively, which are the sole applicable scopes. This assessment follows the guidelines of the GHG Protocol and PCAF (PCAF, 2020, 2022; UNFCC Secretariat, 2022).

Scope 1 emissions arising from diesel combustion in the generator, total 46.34 $tCO_{2\text{-}eq}$/year, while scope 3 emissions amount to approximately 1.65 $tCO_{2\text{-}eq}$/year. The scope 3 emissions are primarily attributed to transportation activities, including monthly fuel deliveries using a medium-sized car and repair and maintenance trips requiring a rented large truck to transport both diesel generators. Each trip involves a round-trip distance of 140 km (70 km each way) to the nearest town. These transportation-related emissions highlight the indirect impacts associated with maintaining and fuelling the generator system. When linked to production output, total GHG emissions correspond to 0.074 $tCO_{2\text{-}eq}$/tonne of goods produced.

The environmental and health impacts associated with the diesel generators powering two maize mills highlight the urgent need for technological optimisations. Necessary improvements to reduce emissions and enhance overall sustainability to address key challenges outlined earlier will be explored in the following sections.

7.3.4.2 Scenario analysis

This scenario analysis investigates energy supply solutions for case study 4, an off-grid maize milling enterprise in Malawi, with each scenario addressing specific energy-related challenges. The study aims to identify sustainable and cost-effective solutions to overcome issues such as high fuel costs, environmental impact, and operational inefficiencies. Three scenarios are evaluated against the current operational setup to demonstrate how each configuration serves distinct purposes.

All three optimisation scenarios are modelled over a 25-year period with a 9% nominal discount rate (Borgstein et al., 2019). While the base case represents the current system, where two diesel generators power the maize milling operations, scenario 1 introduces a solar PV-diesel generator hybrid system. By combining solar PV with the existing diesel generators, this setup aims to reduce diesel fuel consumption. Solar energy powers two electric maize mills during daylight hours, while diesel generators act as backup sources. Scenario 2 transitions to a fully solar PV-based system with battery storage, eliminating diesel dependence. Scenario 2 is divided into two sub-scenarios differing only in battery technology. Scenario 2A considers lead-acid, whereas scenario 2B considers lithium-ion battery technology. The configuration focuses on achieving 100% renewable energy penetration,

significantly reducing GHG emissions and long-term operating costs. In contrast to scenarios 1 and 2, scenario 3 integrates syngas production from maize residues to create a dual-fuel generator system. This biomass-based alternative repurposes agricultural waste, such as husks, cobs, and stalks, into syngas through gasification. The syngas cofiring retrofitted diesel generators reduce diesel consumption while offering a sustainable use for agricultural residues that might otherwise be burned to obtain a low-quality fertiliser or discarded.

Together, these analyses yield actionable insights into viable strategies for improving the enterprise's energy access. Each scenario is presented separately in the following sections to enable a comparison of their technical, economic, and environmental implications.

Scenario 1: Solar PV-diesel generator hybrid system

In the first scenario, a PV fuel-saver system was modelled, a hybrid energy solution, which, in this case, consists of solar PV panels and two diesel generators. In this setup, the existing diesel-powered maize mills remain as a backup solution, complemented by a solar PV system that powers two electric motors, one for maize flour milling and another for grinding maize, whenever possible. The diesel generators and their maize mills operate only when solar power is insufficient.

To implement this hybrid system, it was essential to evaluate the performance and costs of maize mills compatible with solar PV systems by reviewing studies and suppliers in Eastern Africa. Studies revealed that solar-powered mills, including solar PV systems and batteries, are generally priced around 2,500 USD/unit (Efficiency for Access Coalition, 2020). However, many of these mills have insufficient capacities, typically below 40 kg/h, whereas the entrepreneur requires at least 80-125 kg/h. For instance, Agsol, a reputable supplier, offers motors with power requirements of 1.2 kW at a cost of 590 USD/unit, and milling capacities of only 60 kg/h (The Renewables Academy (RENAC), n.d.). For modelling purposes, mills from Productive Solar Solutions were chosen as a reference due to their adequate capacity and compatibility with solar PV systems, featuring brushless direct current (BLDC) motors. Their mills meet the required capacity and are equipped with BLDC motors that offer relatively low power requirements of 1.3 kW, priced at 760 USD/motor unit, including a BLDC motor controller (Productive Solar Solutions, 2024). With a motor base cost of 760 USD, 19% VAT, and transportation and shipping expenses assumed to increase costs by

an additional 30%, the total capital costs for both mills are estimated at 2,351 USD. O&M costs for the electric motors are estimated at 24 USD/year (RENAC, n.d.).

For modelling the solar PV system in HOMER Pro, cost assumptions were primarily based on 2022 supplier quotations provided by a GIZ representative of a GIZ Malawi office. Although these quotations, sourced from a small-scale on-grid project, are not entirely aligned with the year and off-grid context in Malawi, they were considered suitable for this analysis. Due to privacy concerns, the original documents cannot be shared, however, these values were compared against estimates from ESMAP for validation. Key cost components include solar panels priced at 892,857 MWK/kW_p, with installation plus soft costs, adjusted for off-grid transportation (20% increase in quoted labour costs), totalling 761,905 MWK/kW_p. Inverters, quoted at 350,877 MWK/kW, were not included as the solar mills in this case come equipped with DC converters, eliminating the need for additional inverters. The total CAPEX for the solar PV system, including panels, installation, labour, transportation, and taxes, was calculated at approximately 1,626 USD/kW_p, based on the exchange rate used in this study. Operational and maintenance (O&M) costs were set at a standard rate of 10 USD/kW/year (ESMAP, 2022). For comparison, ESMAP estimates the cost of solar PV panels and inverters, excluding soft costs and taxes, at 834 USD/kW_p in Kenya, 585 USD/kW_p in Tanzania, and an average of 631 USD/kW_p for Africa and Asia (ESMAP, 2022). In Malawi, equivalent costs are approximately 1,462 USD/kW_p. However, this value includes taxes and shipment costs, making it not directly comparable to ESMAP estimates, although it excludes soft costs. The higher cost aligns with expectations and justifies the conservative approach adopted in this study.

In the HOMER model, the added solar-powered mills are connected to the DC bus (as a combined load), while the existing diesel-powered mills are connected to the AC bus (as a combined load). Due to HOMER's limitation of two electric loads, the mills powered by PV and the diesel mills were grouped together within their respective energy supply configurations. Additionally, the two diesel generators, which are assumed to run in parallel whenever required, were combined in terms of capacity and fuel consumption. This approach avoids a situation where HOMER might otherwise attempt to run only one generator at a time for cost optimisation, which is not practical for this scenario. Although a BLDC motor controller is already included in the technical setup and cost estimation of the electric motors, HOMER Pro requires the inclusion of an AC-DC converter to model systems with both AC and DC loads. However, in this setup, the diesel generator is intended to power only the AC load, while the solar PV system exclusively powers the DC load,

making an actual converter unnecessary. To work around this modelling constraint, a negligible 1-W AC-DC converter is added to the system at no cost. This ensures that HOMER Pro's requirement for a connection between the solar PV system and the load is fulfilled while preventing the PV system from powering the AC load, thereby maintaining the intended technical configuration, and allowing the simulation to run without compromise[13].

To ensure that the diesel generators operate only when solar power is unavailable, a custom schedule was implemented in HOMER Pro. The generators are set to run during specific hours when solar irradiance is typically low, 2 hours in the early morning (6:00-8:00) and 2 hours in the evening (16:00-18:00). This schedule represents the minimum viable option, as configurations with reduced diesel usage and increased reliance on solar PV without storage lead to significant capacity shortages during these critical periods. An additional test run was conducted with a modified schedule of 3 hours in the morning and 3 hours in the evening. This setup required slightly less PV capacity, leading to marginal reductions in both excess energy production and unmet load. However, these improvements were not significant enough to outweigh the substantially higher operating costs from increased fuel consumption, coupled with a nearly unchanged NPC. As a result, this configuration was deemed impractical and ultimately disregarded. The selected approach achieves a balance between minimising fuel consumption, maintaining a relatively high renewable energy penetration (even with significant excess production), and ensuring economic feasibility. It simplifies operations for an off-grid business, where ease of management is crucial, particularly for users with limited technical training. While a more complex, irradiation-based schedule could enhance efficiency, it would be less practical in real-life scenarios, where solar availability cannot be perfectly predicted. The chosen solution prioritises simplicity, operational reliability, and a cost-effective balance of renewable and conventional energy sources.

As illustrated in Figure 44, the most cost-effective configuration for this scenario includes a 20 kW_p solar PV system added to the base case, alongside the two solar-powered electric motors. This hybrid system significantly reduces fuel consumption while maintaining operational reliability and meeting the load

[13] Although this setup restricts the solar PV from powering the AC load, HOMER Pro models a small flow (approximately 1 kWh/year) from the converter to the diesel-powered mills. This discrepancy is negligible in terms of system performance and does not affect the technical integrity of the simulation.

requirements without any battery storage. The solar PV system is designed solely to supply the solar-powered mills, and excess electricity produced is curtailed, with no consideration given to additional demand in this scenario[14].

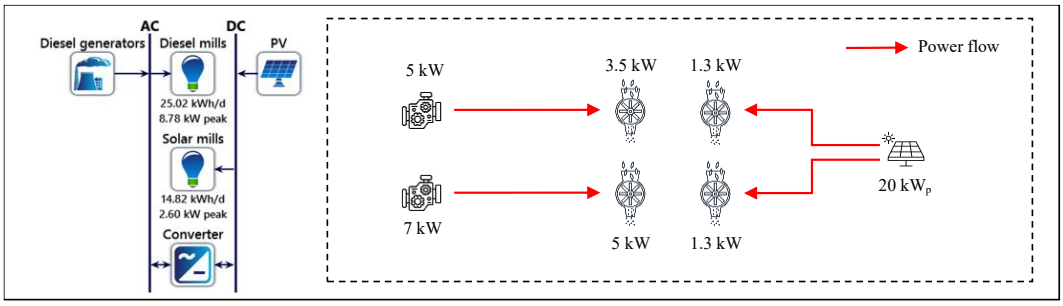

Figure 44. Case study 4: Technical setup of scenario 1

Notes: The left graphic was modelled with HOMER Pro (including calculated values), and the right graphic was modelled by the author (including rounded values).

Abbreviations: kW = kilowatt; kWh/d = kilowatt-hour per day; kW_p = kilowatt peak; PV = photovoltaic

In scenario 1, the energy supply is shared between two diesel generators and the solar PV system, achieving a renewable fraction of approximately 37%. In other words, the diesel generators produce 9,131 kWh/year, supplying the diesel-powered mills for 4 hours per day on weekdays. The solar PV system generates 33,309 kWh/year, of which only 5,264 kWh/year is useful energy consumed by the solar-powered mills, and the remaining 66% is surplus electricity being curtailed. The solar PV system cannot meet 1% of the solar mill load annually (146 kWh/year) due to insufficient solar irradiation during the set operational schedule. This issue is more pronounced during the rainy season (November to March/April) and less significant but occasional in the dry season (April to October) when operations due to harvesting and the need for processing are more critical (USAID & Famine Early Warning Systems Network (FEWS NET), 2024). Even with an increase in PV capacity to 100 kW_p, a residual 0.5% shortage remains, indicating the difficulty of fully meeting load requirements with solar PV alone without any storage system.

[14] In the future, potential additional demand that could utilise the excess electricity could be investigated. It is important to note that in the off-grid setting, with the majority of villagers not using electricity or having any electrical or mechanical demand, this would require further assessment and analysis beyond the scope of this study.

In practice, the diesel generators would compensate for this gap, but this adjustment is not modelled and is considered a minor limitation.

Scenario 1 results in a significant reduction in diesel fuel use, lowering consumption to 6,067 L/year, a 67% decrease compared to the base case. Moreover, the diesel generators operate for only 1,040 hours annually, which potentially extends their operational lifespan to over 19 years (based on a 20,000-hour lifespan), requiring only one replacement during the project period.

Over a 25-year period, using a 9% discount rate, the system achieves an NPC of 117,806 USD. The total upfront capital cost is 34,867 USD, representing 30% of the NPC, with the majority attributed to the CAPEX of the solar PV system. Fuel costs account for the largest share of approximately 64% of the total NPC, with O&M of the diesel generators contributing another 4%. Compared to the base case, scenario 1 demonstrates a 52% reduction in NPC, highlighting the economic benefits of the hybrid system. Operating costs have decreased by 66%, now amounting to 8,444 USD/year.

The environmental impact in scenario 1 demonstrates a marked improvement, due to a 67% reduction in fuel consumption compared to the base case. This translates to a 67% decrease in total GHG emissions, equivalent to 799.75 $tCO_{2\text{-}eq}$ avoided over the project's 25-year lifetime. Annual emissions have been reduced to 16 $tCO_{2\text{-}eq}$/year, encompassing both generator emissions and transportation-related activities. The reduction in transportation needs is assumed to be proportional to the decrease in fuel consumption, resulting in fewer fuel deliveries and less frequent generator maintenance trips.

Scenario 2: A fully solar PV-based system with battery storage

Building on the hybrid approach in scenario 1, scenario 2 eliminates reliance on diesel generators entirely. A solar PV system is paired with battery storage, powering the solar maize mills when needed (12 hours/day on weekdays). While the diesel-powered maize mills remain available as a backup, they were excluded from the HOMER Pro simulation, with only their salvage value included in the economic analysis.

The same maize mills from scenario 1 were connected to the DC bus in this setup. Unlike in scenario 1, their operation was modelled as two separate electric loads in HOMER Pro to reflect realistic usage patterns. These loads were treated as

equally critical, with a capacity shortage tolerance set to 0%, ensuring continuous operation by either the solar PV system or the battery storage throughout the year. Since the BLDC motor controllers are already integrated into the technical setup and costs of the electric motors, no additional converters were needed in the system design.

The CAPEX of the solar PV system remains consistent with scenario 1. In contrast, scenario 2 incorporates two sub-scenarios: scenario 2A, which includes lead-acid battery storage, and scenario 2B, which utilises lithium-ion battery storage. The cost assumptions for battery storage are derived from different sources. For lead-acid batteries, an average cost of 153 USD/kWh is adopted from ESMAP estimates for the Africa/Asia region. However, for lithium-ion batteries, cost estimates from potential suppliers, as provided by a GIZ representative working in a Malawi programme, are used. The lithium-ion battery storage cost is estimated at 491 USD/kWh, which is slightly higher than the ESMAP regional average of 455 USD/kWh (ESMAP, 2022). This estimate is considered more realistic and contextually accurate for the case study, reflecting market conditions and supplier pricing in Malawi. Battery lifespan is assessed based on energy throughput. Lead-acid batteries provide 800 kWh of throughput with 60% DoD and 80% efficiency, yielding 384 kWh of usable energy before replacement. Lithium-ion batteries last longer, with 3,000 kWh of throughput, 80% DoD, and 90% efficiency, providing 2,160 kWh of usable energy. Given real-world factors affecting longevity, a conservative lifespan of 5 years for lead-acid and 10 years for lithium-ion batteries is assumed, aligning with the literature (Kebede et al., 2021; C. Zhang et al., 2017; X. Zhang et al., 2021).

As shown in Figure 45, the optimal configuration according to HOMER Pro includes a 10 kW_p solar PV system with 90 kWh lead-acid battery storage in scenario 2A, compared to 65 kWh lithium-ion battery storage in scenario 2B, delivering an autonomous and sustainable energy solution.

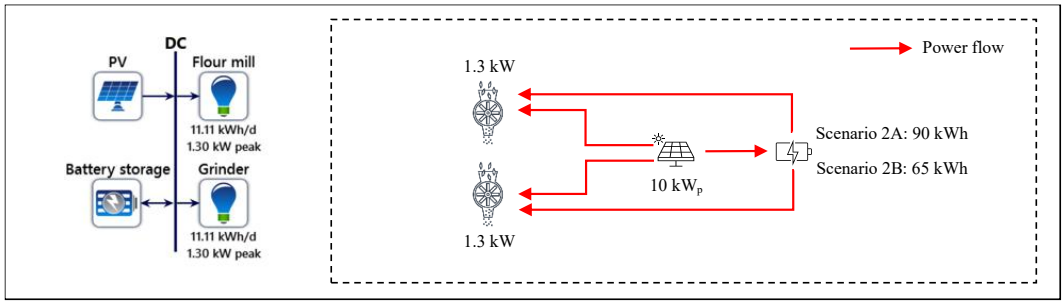

Figure 45. Case study 4: Technical setup of scenario 2

Notes: The left graphic was modelled with HOMER Pro, and the right graphic was modelled by the author. Scenario 2A contains lead-acid battery storage, while scenario 2B contains lithium-ion battery storage

Abbreviations: kW = kilowatt; kWh/d = kilowatt-hour per day; kW_p = kilowatt peak; PV = solar photovoltaic

In scenario 2, the energy supply is fully derived from the solar PV system with battery storage, achieving a 100% renewable fraction. Combined, the two solar mills consume 8,112 kWh/year. The minimal fraction of 0.06% and 0.09% of demand not met by the system in scenarios 2B and 2A, respectively, is negligible. The solar PV system generates 16,655 kWh/year, of which around 49-50% is excess electricity which can neither supply the demand directly nor be stored in the battery system. Compared to scenario 1, excess electricity is reduced by 16 percentage points. Both battery systems in scenarios 2A and 2B are autonomous for 56-58 hours.

Over 25 years, assuming a 9% discount rate, scenario 2 achieves a 70-75% reduction in NPC and approximately a 90% decrease in operating costs compared to the base case. Scenario 2A, which utilises lead-acid battery storage, results in the lowest NPC, while operating costs remain nearly identical to scenario 2B, with only a marginal 2% difference (88% reduction in scenario 2A vs. 90% in scenario 2B). The initial investment constitutes 52% of the NPC in scenario 2A and 68% in scenario 2B, underscoring the higher upfront costs associated with lithium-ion battery technology. Conversely, replacement costs account for 34% of the NPC in scenario 2A but only 26% in scenario 2B, reflecting the longer lifespan of lithium-ion batteries. The remaining costs primarily stem from O&M expenses related to the PV and battery storage systems.

The environmental impact of scenario 2 represents a significant improvement, as it is considered emission-free during operation, relying solely on solar PV and lithium-ion battery storage.

Scenario 3: Dual fuel use generator with diesel and syngas

Scenario 3 explores an alternative approach to the replacement strategies proposed in scenarios 1 and 2, which focused on integrating a solar PV system. In this scenario, the maize residues currently burned in open fields and used as low-quality fertiliser, such as husks, cobs, and stalks, are assumed to be collected and processed in a gasifier to produce an energy-rich gas called synthesis gas (herein referred to as syngas) (Bi Aslam, 2022; Branca et al., 2014b; Gao et al., 2023). The syngas is then used to power retrofitted diesel generators, capable of operating on both diesel and syngas. These so-called dual-fuel generators are used as a practical solution based on existing practices and infrastructure. This approach is particularly suitable given the uncertainty about the precise amount of maize residue available for energy production. This solution leverages the ease and low cost of retrofitting existing diesel generators to operate with syngas, allowing for a more sustainable energy generation process while maintaining operational flexibility (Bi Aslam, 2022; Ray et al., 2013).

Gasification technology was chosen over AD in this case study due to the suitability of the available biomass feedstock. Low-moisture agricultural residues, such as maize husks, cobs, and stalks, are better suited for gasification (Bi Aslam, 2022; Gao et al., 2023).

In HOMER Pro, cofired generators operate on a mixture of fossil fuel and biogas. In HOMER Pro, biogas is defined as gasified biomass, referring to the gaseous fuel produced from biomass feedstock, such as wood waste, agricultural residues, or energy crops, through either thermochemical or biological processes. However, it is important to note that while HOMER refers to this as “biogas”, the term “syngas” is used here to reflect the gas utilised in this scenario.

HOMER Pro calculates the generator’s output and the corresponding fuel mass flow rates at each time step, adhering to several key assumptions. First, the syngas substitution ratio is constant, regardless of engine output power or fuel mixture. The substitution ratio in co-fired generators in HOMER Pro represents the proportion of syngas that replaces fossil fuel, based on the LHV of the fuels utilised. For this scenario, the substitution ratio is estimated at 8.79, based on the ratio of the LHV

of diesel (43 MJ/kg) to that of syngas (4.89 MJ/kg). The latter value represents an average derived from the literature (Bi Aslam, 2022). Secondly, the minimum fossil fuel fraction is assumed at 20%, in line with HOMER's default settings and literature recommendations (Bi Aslam, 2022). Thirdly, the generator's derating factor, which represents the maximum power output a cofired generator can achieve when operating at the minimum allowable fossil fuel fraction, expressed as a percentage of its rated capacity, is kept at the default value of 70%. Despite this derating, the generator can operate at the full-rated power if the fossil fraction is sufficient. It should also be noted that HOMER Pro's algorithm is set to prioritise the use of syngas to minimise fossil fuel consumption.

During the interview, an assessment of the amount of maize residue disposed of and burned in open fields was not possible to quantify by the village representatives. Therefore, an estimate was made regarding the amount needed to satisfy the energy demand of the enterprise, assuming the use of a dual-fuel generator. The first assumption regarding the biomass feedstock is that only maize residues deemed unsuitable for human or animal consumption are collected for gasification. These are typically the residues burned as low-quality fertiliser in fields across the village. The second assumption concerns the cost of these residues: while these residues are generally available at no cost, a fee of 55 USD/tonne is applied to account for purchase, collection, and transportation expenses. This fee also reflects potential resistance from the local community, as the residues may be perceived as low-value fertiliser, necessitating compensation to encourage their availability for energy production. This rate is at the lower end of what is suggested by the IRENA Secretariat (2012). Finally, to estimate the amount of maize residue required for this setup, the gasification ratio, defined as the ratio of syngas generated to biomass consumed in the gasifier, was determined at 2.29. This ratio, derived from the LHV of syngas relative to maize residues and assuming a gasifier efficiency of 70% (Gao et al., 2023) is based on a conservative LHV value of 16 MJ/kg for maize residues (Bi Aslam, 2022; Ray et al., 2013). Using this ratio, HOMER Pro calculates the annual biomass feedstock requirement to be just over 47 tonnes per year of maize residue, equating to approximately 190 kg per day over 260 working days. The gasifier is assumed to operate on the same schedule as the diesel generators, 12 hours per day on weekdays, which is considered feasible given the context. This results in an estimated gasifier capacity of approximately 67.5 kW. The economic considerations for the gasifier were based on literature, which suggests the cost of a gasification system typically ranges from 2,000 to 5,500 USD/kW of installed capacity (Lourinho et al., 2023). These estimates provide a

framework for understanding the potential capital investment required for the gasifier system.

As shown in Figure 46, the optimal configuration for scenario 3 includes a gasifier with a capacity of 67.5 kW, utilising around 47 tonnes of maize residues per year. The two diesel generators are retrofitted to dual-fuel operation, running on a combination of diesel and syngas.

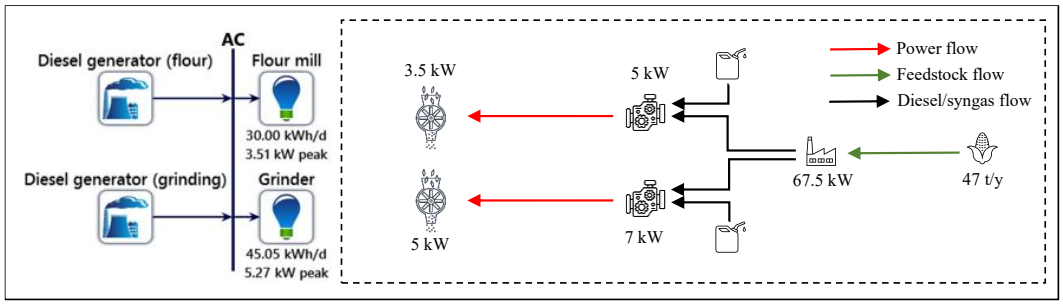

Figure 46. Case study 4: Technical setup of scenario 3

Notes: The left graphic was modelled with HOMER Pro, including calculated values, and the right graphic was modelled by the author, including rounded values.

Abbreviations: kW = kilowatt; kWh/d = kilowatt-hour per day; t/y = tonne per year

In Scenario 3, the energy supply is provided by dual-fuel generators operating on a combination of diesel and syngas, achieving a renewable fraction of approximately 76%. This translates to approximately 6,619 kWh of energy supplied at an average generator efficiency of around 15%, with the remainder of the energy derived from syngas produced from maize residues. Consequently, diesel consumption is significantly reduced, with only 4,413 L/year now required.

From an economic standpoint, scenario 3 incurs an NPC that is 96% higher than the base case, totalling 484,801 USD at a 9% discount rate over 25 years. The initial investment for a gasifier and retrofitting the diesel generators accounts for almost 54% of the NPC, while another 25% are attributed to the gasifier O&M costs. Fuel costs for diesel and feedstock account for a considerable 17%, and an additional 4% stems from the dual fuel generator's O&M costs. The initial investment is primarily driven by the gasifier, which constitutes 52% of the NPC. The retrofitting costs were estimated based on the following breakdown: 300 USD/kW for the syngas injection system, 100 USD/kW for labour and setup, and 30 USD/kW for transportation and delivery. Machinery is exempt from VAT in Malawi

(PricewaterhouseCoopers (PwC), 2024); however, a 20% markup was applied to cover overheads and unforeseen expenses, with an additional 10% contingency bringing the total to 567.6 USD/kW. The O&M costs for the dual-fuel generators are estimated to increase by 30% compared to single-fuel generators due to the need for specialised expertise, additional oversight, and potentially more frequent maintenance. The O&M expenses for the gasifier are based on an estimation that annual O&M expenses represent 3-6% of the gasifier's CAPEX, supplemented by an additional operating cost of 3.5 USD/MWh of energy generated by the gasifier[15] (Lourinho et al., 2023). This dual cost structure reflects both fixed maintenance requirements and variable costs tied to syngas production. Despite the higher CAPEX, operating costs, now totalling 22,943 USD/year, have decreased by 9% compared to the base case, primarily due to reduced diesel consumption. Despite the relatively high initial investment associated with scenario 3, it presents an opportunity to not only yield modest annual economic savings but also to mitigate the practice of open-field burning, which often results in the use of low-quality fertiliser with environmental and health impacts.

The environmental impact assessment of scenario 3 reveals significant improvements through a substantial reduction in diesel usage, leading to lower GHG emissions. Specifically, scope 1 GHG emissions decrease by approximately 76%, equivalent to 877.5 $tCO_{2\text{-}eq}$ of direct GHG emissions avoided over the project's lifetime. When incorporating scope 3 emissions, which account for GHG emissions from fuel transportation and travel for maintenance, the former is assumed to decrease proportionally with reduced fuel consumption, while the latter is assumed to remain constant compared to the base case. Avoided scope 3 emissions are minimal, amounting to 0.96 $tCO_{2\text{-}eq}$/year. Overall, the total GHG emissions avoided from scope 1 and scope 3 due to reduced diesel consumption are estimated at 901.75 $tCO_{2\text{-}eq}$ over the project's lifetime.

Net GHG emissions from the gasifier and syngas combustion are considered negligible for CO_2, in line with IPCC and GHG Protocol guidelines for short-lived biogenic material (Rypdal & Paciornik, 2006). The maize residue feedstock operates within a short-term crop cycle, where carbon released during combustion is reabsorbed during subsequent growth, creating a closed carbon loop. This aligns

[15] These costs are based on estimates provided in EUR by (Lourinho et al., 2023): annual O&M expenses representing 3-6% of the gasifier's CAPEX (1965-5235 EUR/kW) and an operating cost of 3.4 EUR/MWh of energy generated by the gasifier. A 1.04 USD/EUR conversion rate was applied to express these values in USD.

with bioenergy emissions accounting methodologies, which treat sustainably managed biomass as carbon-neutral, highlighting the environmental benefits of syngas from maize residues. Other emissions from syngas combustion, including but not limited to nitrogen oxides (NO_x), sulphur oxides (SO_x), carbon monoxide (CO), and particulate matter (PM), are excluded from this assessment due to the limited availability of context-specific emission factors (Whitty et al., 2008). These non-CO_2 emissions are highly variable, influenced by factors such as syngas composition, gasifier design, and operating conditions.

Scenario analysis summary

The analysis explored three alternative energy scenarios to replace the base case, which relies entirely on diesel generators for powering maize mills. Each scenario presented distinct advantages and challenges, offering a spectrum of solutions to improve economic efficiency and environmental sustainability.

Scenario 1 introduced a hybrid system that combines solar PV with diesel generators, maintaining operational familiarity while achieving modest improvements in cost efficiency and emissions reductions. It serves as a practical step toward integrating renewable energy without significant disruption to current practices. Scenario 2 represented the most sustainable and cost-effective option, replacing the diesel generators entirely with a solar PV system equipped with battery storage while distinguishing between lead-acid and lithium-ion technology. This configuration significantly reduced operational costs and environmental impact, offering a highly favourable solution for long-term benefits. Noteworthy is scenario 2A, which replaced diesel backup with lead-acid battery storage, demonstrating that with a similar initial investment as scenario 1, the system can achieve nearly a 50% reduction in NPC and over a 60% decrease in operating costs. Additionally, this transition eliminates GHG emissions, significantly enhancing the system's environmental sustainability. Scenario 3 takes a different approach, retrofitting the existing diesel generators for dual-fuel operation using syngas produced by a gasifier. While this system reduces reliance on diesel and still lowers operational costs compared to the base case, it involves higher upfront costs and greater complexity due to the installation and operation of a gasifier. This scenario may appeal to those seeking a transitional solution that leverages existing infrastructure but requires careful consideration of its financial and technical demands. Table 27 summarises the main indicators for each scenario compared to the base case.

Table 27. Case study 4: Comparison of initial investment, NPC, annual operating costs and GHG emissions between base case and scenarios 1-3

	Initial investment	NPC	Operating costs	GHG emissions
Unit	USD	USD	USD/year	$tCO_{2\text{-}eq}$/year
Base case	0	247,500	25,200	47.99
Scenario 1	34,900	117,800	8,400	16.00
Scenario 2A	32,400	62,700	3,100	0.00
Scenario 2B	50,500	74,700	2,500	0.00
Scenario 3	259,400	484,800	22,900	11.92

Notes: All cost figures in USD are rounded to the nearest hundred to enhance readability and facilitate comparison.

Abbreviations: $tCO_{2\text{-}eq}$ = tonne of carbon dioxide equivalent; GHG = greenhouse gas; NPC = net present cost; USD = United States dollar

In conclusion, the scenarios reflect a balance between immediate feasibility and long-term sustainability. Scenario 2 stands out as the most transformative and impactful, while scenario 1 provides a less disruptive but incremental improvement. Scenario 3 offers a different approach with potential benefits but demands significant investment and adaptation. The best-suited choice depends on the entrepreneur's goals, resources, and readiness to adopt new technologies.

7.3.4.3 MTF evaluation

This chapter evaluates the three distinct enhancement scenarios discussed in the previous section according to the World Bank's MTF.

To systematically assess these scenarios, it is essential to clarify the energy classification applied. According to the MTF, energy access is classified by the form of energy used at the point of service, rather than by the number or type of fuels utilised (Bhatia & Angelou, 2015). In the base case, the maize mill is powered

directly by a diesel engine, which transmits mechanical energy through belt-driven shaft rotation (Agason Motors, 2025). Since no electricity is generated or used, this setup falls under the fuel-based motive power category. Scenario 1 adds a solar PV-powered electric mill alongside the diesel system, combining both fuel and electricity categories. Scenario 2 involves full electrification, with milling powered entirely by electricity, placing it solely under the electricity category. In scenario 3, the diesel engine is modified to operate with both diesel and syngas but still delivers mechanical power directly. As no electricity is used, this remains in the fuel-based motive power category.

Regarding capacity, the base case already achieved tier 5 requirements, and this remains unchanged in scenarios 1 and 3. Scenario 2, however, transitions to a fully electric setup that continues to meet tier 5 criteria with installed capacity exceeding the 2-kW threshold. Availability assumptions across scenarios consider the realistic context of seasonal diesel supply fluctuations, typically lasting about three months each year (Engel et al., 2025; Gad & Leone, 2025; Kampanje, 2012; Mhone, 2024, 2025). It is assumed that the enterprise manages these periods by obtaining the necessary annual fuel supply within the nine months when diesel is consistently available. Scenario 1 significantly reduces diesel consumption by more than 50% relative to the base case, making this assumption easily achievable. Scenario 3 further lowers annual diesel requirements, enhancing the practicality of fuel procurement within the available window. Additionally, scenario 3 assumes uninterrupted year-round availability of biomass for gasification. Electric supply availability in scenarios 1 and 2 is quantitatively assessed, with scenario 1 experiencing minor shortages of around 1%, and scenario 2 having even fewer interruptions at less than 0.1%, ensuring high availability.

Reliability criteria under the MTF are met across all scenarios. Specifically, scenario 1 experiences approximately 1.5 hours of weekly outages associated with the solar PV system, yet still fulfils tier 5 requirements. Scenario 2 demonstrates superior reliability with minimal outages ranging from 3 to 5 min/week. Based on the availability assumptions previously outlined, non-electric energy demand is assumed to be fully met by either diesel or syngas without disruptions or shortages. Affordability is evaluated with scenarios 1 and 2 achieving tier 5 standards specifically for their electric supply, as these costs remain at or below grid tariffs. Diesel fuel, however, is substantially costlier (more than twice grid tariff costs), limiting the fuel component in scenario 1 to tier 3 affordability. Scenario 3, blending biomass-derived syngas and diesel, achieves better cost efficiency (approximately 1.5 times the grid tariff), reaching tier 4 affordability. Convenience attributes are

favourable in scenarios 1 and 2, assuming tier 5 performance for electric supply. Specifically for scenario 1, reduced fuel usage and potentially lower operational and maintenance requirements are assumed to elevate fuel collection and delivery convenience to tier 5, indicating little to no impact compared to the moderate impact evaluated in the base case. Scenario 3 is considered neither significantly improving nor worsening convenience compared to the base case; reduced fuel requirements are offset by increased operational and maintenance demands, maintaining a moderate impact. Health ratings for solar PV-based electricity in scenarios 1 and 2 are tier 5 due to zero GHG emissions. However, diesel used outdoors in scenario 1 and the diesel-syngas blend in scenario 3 limit their non-electric components to a tier 3 rating. Safety conditions remain consistent with the base scenario across all evaluated enhancements.

Figure 47 illustrates the evolution of energy access tier performance for the Malawian case study from the base case through scenarios 1 to 3, according to the World Bank's MTF. The base case initially shows moderate overall performance at tier 3, primarily constrained by health and affordability attributes associated with diesel use. Scenario 2 achieves the highest improvement, reaching an overall maximum tier 5 performance by fully transitioning to a solar PV system with battery storage, significantly enhancing health, availability, reliability, and affordability attributes. Although scenarios 1 and 3 maintain an overall tier 3 performance, largely due to continued diesel use impacting the health attribute, both scenarios demonstrate enhanced availability and reliability through strategic diesel fuel procurement and storage during periods of availability. Notably, scenario 1 also attains tier 5 for its electric supply due to the integration of solar PV, highlighting the substantial benefits achievable even without complete diesel elimination.

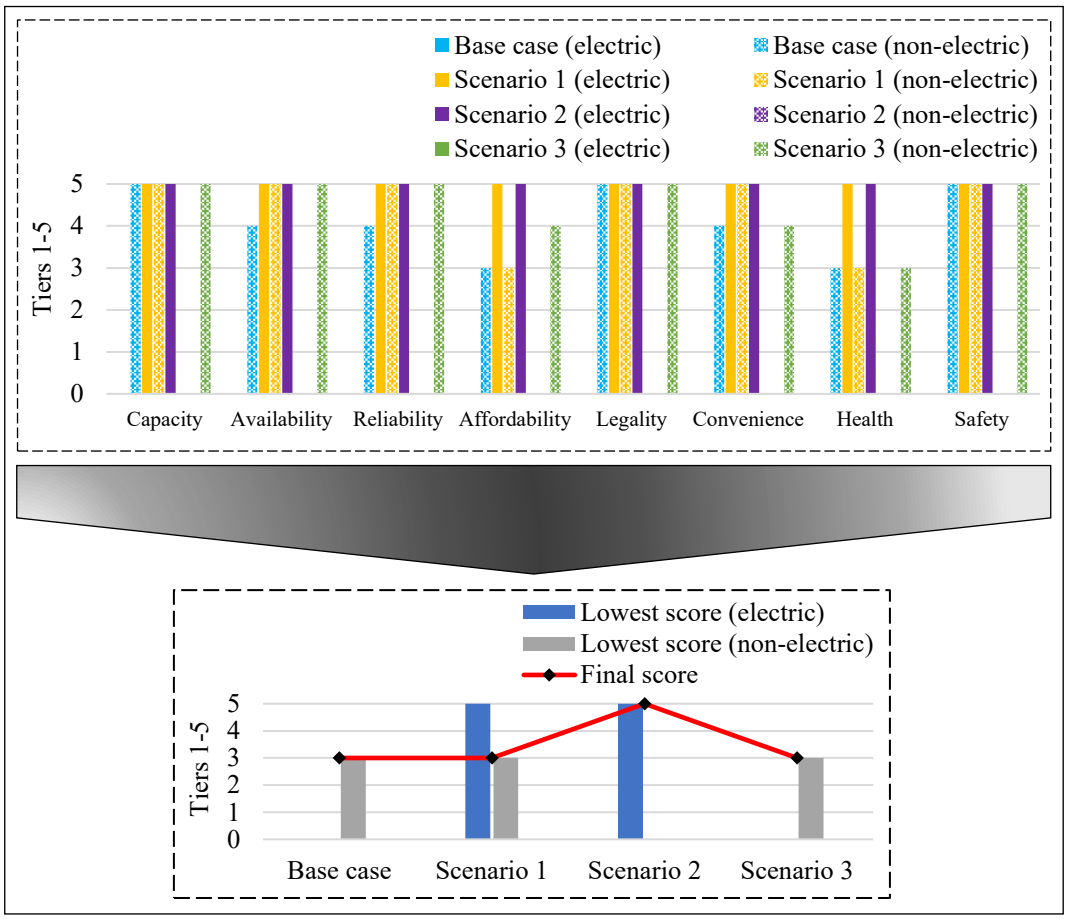

Figure 47. Case study 4: MTF tier performance comparison between base case and scenarios 1-3

Notes: The absence of an assessment for electric energy sources in the base case and scenario 3, as well as for non-electric energy sources in scenario 2, does not indicate tier 0 performance. Rather, it reflects the inapplicability of the respective energy source to those scenarios.

The findings from this analysis underscore the substantial benefits derived from transitioning to renewable energy systems, with scenario 2 exemplifying the potential of achieving full energy autonomy and maximum tier performance. Nevertheless, the results also illustrate that meaningful improvements, particularly in reliability and availability, can still be realised in scenarios partially reliant on diesel, provided strategic fuel management practices are employed. These outcomes highlight the importance of tailored renewable energy strategies and resource management in enhancing overall energy access.

7.3.5 Case study 5: Nigeria – Footwear manufacturing

Case study 5 profiles a for-profit women-owned enterprise located in Lekki, Lagos, Nigeria. The business is led by a sole female entrepreneur who specialises in leather footwear manufacturing, producing approximately 65 pairs per month. A small volume of wearing apparel production (3 kg/month) complements the primary activity, while daily paper waste remains minimal at just 0.25 kg/day. Recently, the entrepreneur expanded operations by opening a dedicated retail shop. This shop not only markets her own products but also functions as a local platform, showcasing goods from other female entrepreneurs in areas such as self-care, beauty, hygiene, ceramics, accessories, and home décor. The business maintains a strong monthly profit margin of 69%, underscoring its commercial viability.

Despite this success, the entrepreneur faces considerable challenges. Operational disruptions caused by frequent grid outages remain a central constraint. Other persistent obstacles include irregular raw material supply and the need to uphold high product standards through intensive quality control. From a gendered perspective, she reports regularly encountering biased perceptions that compel her to prove her competence, alongside more serious issues such as harassment when interacting with authorities.

Her motivation to transition to renewable energy is grounded in a desire to operate more sustainably and independently. Priorities include improving the availability and predictability of energy supply, reducing reliance on fossil fuels, and eliminating the air and noise pollution associated with generators. However, she also cites key barriers to renewable adoption: limited access to tailored financing, a lack of technical knowledge and reliable technology providers, and uncertainty surrounding the regulatory environment. Despite these obstacles, the entrepreneur expresses a willingness to pursue renewable energy solutions through a structured loan mechanism, estimating a feasible monthly repayment of around 100 USD.

Using the World Bank's MTF, the enterprise was assigned an overall energy access tier of 3. This reflects chronic deficiencies in grid availability and reliability, further compounded by challenges in sourcing backup fuel and operating backup generators.

This enterprise profile provides critical context for understanding the energy access realities within this sole female-owned Nigerian enterprise. What follows is

a detailed baseline assessment of the current energy system, including its technical and economic configuration and environmental impact. This baseline serves as the reference point against which the viability of tailored energy enhancement strategies will be evaluated.

7.3.5.1 Base case

Energy use across the enterprise is characterised by a multi-carrier system adapted to different operational needs. At the production site, grid electricity functions as the primary power source, complemented by LPG for thermal applications and a petrol generator that mitigates the impact of frequent grid outages, reported to exceed 11 hours per week. Core productive processes include drying, ironing, sewing, and moulding, all of which require a stable and versatile energy supply to maintain workflow efficiency.

At the retail shop, the energy profile differs significantly. While the shop is also connected to the national grid, the frequent power cuts necessitate regular reliance on a diesel backup generator to maintain operations. The main electricity demands stem from air conditioning, refrigeration, lighting, and office equipment, key functions for ensuring customer comfort and preserving product quality.

Energy expenditures reflect these operational dynamics. At the production site, the entrepreneur incurs approximately 72 USD/month in monthly energy costs. In contrast, the retail shop, generates a significantly higher monthly energy expense of about 460 USD/month.

Table 28 outlines the core productive processes and associated energy-consuming appliances across both sites. At the production facility, heating and ironing stand out as the most temperature-intensive operations, requiring reliable thermal input. Meanwhile, energy demand at the retail outlet is met exclusively through electricity, predominantly for air conditioning and refrigeration.

Table 28. Case study 5: Summary of productive use applications

Process	Temperature	Energy carrier	Appliance		Power rating or consumption	
	°C	Type	Count	Type	Value	Unit

Filling	-	Grid electricity; Petrol-based electricity	2	Filler machine	0.55	kW
Heating	50	Grid electricity; Petrol-based electricity	1	Blow dryer	2	kW
	130-180	Grid electricity; Petrol-based electricity	1	Stamping machine	0.8	kW
Ironing	110-180	Grid electricity; Petrol-based electricity	1	Iron	0.8	kW
Moulding	50	LPG	1	Burner	14.2	kg/month
Sewing	-	Grid electricity; Petrol-based electricity	3	Sewing machine	0.25	kW
Air conditioning	18-21	Grid electricity;	3	AC	1.12	kW
		Diesel-based electricity	1	AC	0.71	kW

Notes: At the retail shop, besides the air conditioning listed in the table, some minor electric demand stems from office equipment, refrigeration, and lighting, which are not listed above.

Abbreviations: °C = degree Celsius; AC = air conditioning; kg = kilogramme; kW = kilowatt; LPG = liquified petroleum gas

Understanding the specific functions and energy uses of each appliance across the two sites offers a clearer picture of how and when energy is consumed. This mapping of thermal and electrical processes provides the basis for characterising the enterprise's daily demand profile (see Appendix D for more details), revealing key operational patterns and pinpointing critical periods of energy intensity.

At the production site, operations are limited to working hours between 9:00 and 16:30, Monday to Friday. Similarly, the retail shop follows a comparable schedule but remains open six days per week to accommodate weekend events, such as markets where local female entrepreneurs showcase and sell their products. The production site relies on several electrical appliances, including a blow dryer (2 kW) operating for less than one hour per day, an iron (0.8 kW) used for two hours daily, and a stamping machine (0.8 kW) running for one hour per day but only twice a week. Additionally, an overlock machine (0.25 kW) is used for two hours daily, four days per week, while two sewing machines (0.25 kW each) operate for three hours per day, four days per week, between 13:00 and 16:00. Two filler machines (0.55 kW each) function for five hours daily, Monday to Friday. Beyond electrical demand, the facility requires thermal energy supplied through an LPG burner, operating for two hours per day, four days per week. As a result, the production site records a monthly electricity demand of approximately 200 kWh/month from the grid, supplemented by an additional 149 kWh/month from a backup petrol generator. The total annual electricity consumption reaches 4,183 kWh/year, while thermal energy demand amounts to 674 kWh/year, derived from 170 litres of LPG. This calculation is based on an LHV of LPG of 47.3 MJ/kg, a burner efficiency of 57%, and an LPG density of 0.53 kg/L (Garg et al., 2006; Islam et al., 2022; Shen et al., 2018; Statistics Netherlands, 2025).

At the retail shop, energy demand is primarily driven by four air conditioning units, lighting, and office equipment, all assumed to operate consistently from Monday to Saturday for eight hours daily. The refrigerator is assumed to be connected year-round but operates in an intermittent cycle, averaging five hours of active runtime per day as it cycles on and off to maintain internal temperatures (Bhatia & Angelou, 2015). This results in an average monthly electricity consumption of 178 kWh/month from the grid, complemented by 1,129 kWh/month supplied by a diesel generator during grid outages. Consequently, the retail shop's total annual electricity consumption amounts to 15,677 kWh/year. The technical setup, including both locations, is presented in Figure 48.

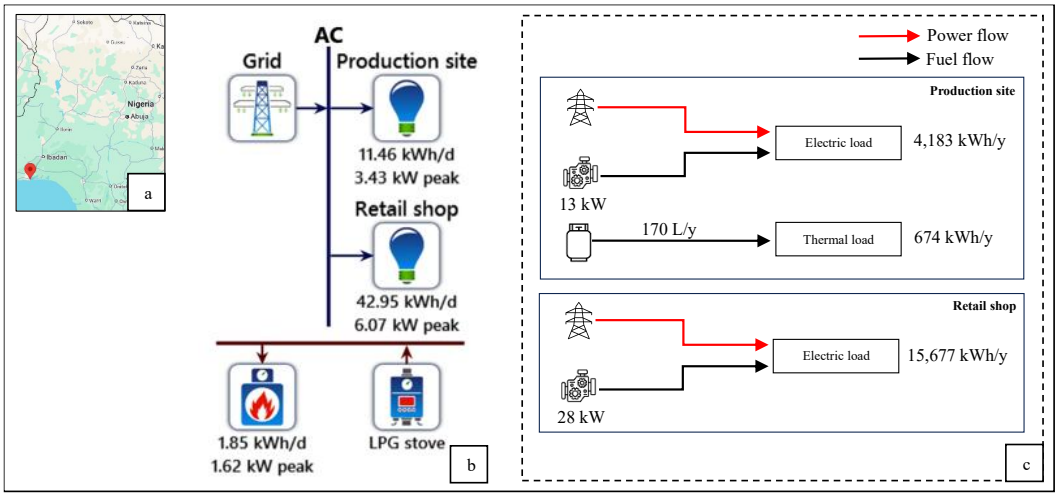

Figure 48. Case study 5: Technical setup of the base case

Notes: a) Geographic location, source: google.maps; (b) Technical setup designed using HOMER Pro, backup generators are not displayed separately due to software limitations; however, the electric load is calculated based on the demand that they cover during grid outages; c) Technical setup designed by the author.

Abbreviations: kW = kilowatt; kWh/d = kilowatt-hour per day; kWh/y = kilowatt-hour per year; LPG = liquified petroleum gas; L/y = litre(s) per year

Assuming a nominal discount rate of 6.86% (Mas'ud et al., 2024) and a project lifetime of 25 years, consistent with common values found in the literature for hybrid and renewable energy projects (Diemuodeke et al., 2021; Mas'ud et al., 2024; Taylor et al., 2023), the base case results in an NPC of 85,757 USD and operating costs of 7,266 USD/year. The majority of these costs stem from the unreliable grid supply, necessitating frequent use of a diesel backup generator at the retail shop. Diesel fuel alone accounts for 46% of the NPC. Petrol fuel required at the production site contributes less than 6% of total costs, while grid electricity itself represents around 38% of the NPC, further underscoring the economic burden and unreliability of the current energy carriers. O&M costs related to both generators contribute another significant 10% of NPC. Thermal demand is minimal, accounting for only around 1% of the NPC.

The LPG burners were assumed to have a lifespan of 10 years and a replacement cost of 25 USD per unit, requiring two replacements over the project's duration (Shaik et al., 2022). However, given their negligible contribution to overall costs, their financial impact is insignificant. Furthermore, neither generator is expected to require replacement within the 25-year analysis period, given that their operational schedules remain well within the 20,000-hour design lifetime, with their

discounted salvage value being deducted from the NPC. The complete cost breakdown by energy carrier is presented in Table 29.

Table 29. Case study 5: Net present cost and operating costs of the base case

Component	NPC (USD)	Operating costs (USD/year)	Share of NPC (%)
Energy carrier			
LPG	1,228	104	1%
Petrol	4,998	424	6%
Diesel	39,456	3,343	46%
Grid electricity	32,673	2,768	38%
O&M of petrol and diesel generators	8,605	729	10%
Total salvage value	-1,221	-104	-1%
Total	**85,757**	**7,266**	**100%**

Notes: A nominal discount rate of 6.86% is applied and the project lifetime is set for 25 years. The replacement costs of the LPG burner are not shown in this figure, as their contribution is negligible at just 0.02%. However, they were included in the total calculations for completeness. Due to rounding, the sum of individual items may not exactly match the total. The total value, however, reflects a more accurate value.

Abbreviations: % = percent; LPG = liquified petroleum gas; NPC = net present cost; O&M = operation and maintenance; USD = United States dollar

Beyond the financial implications, dependence on fossil fuels also carries considerable environmental consequences. To ensure a comprehensive analysis of emissions stemming from energy use at both the production site and the retail shop, direct and indirect GHG emissions across scopes 1 and 2 were assessed, following the GHG Protocol and PCAF guidelines (PCAF, 2020, 2022; UNFCC Secretariat, 2022).

Scope 1 emissions, which originate from the combustion of LPG, petrol, and diesel in burners and generators, amount to 13.05 $tCO_{2\text{-}eq}$/year. The majority of these emissions, approximately 89%, are attributed to diesel combustion at the retail shop, highlighting the significant environmental cost of relying on backup power. Scope 2 emissions, which result from grid electricity use at both locations, contribute an additional 1.79 $tCO_{2\text{-}eq}$/year. Over the 25-year project lifetime, total emissions from both scopes reach 371 $tCO_{2\text{-}eq}$, translating to an emissions intensity of 18.19 $tCO_{2\text{-}eq}$ per tonne of goods produced.

Given the relatively high emissions footprint, particularly from diesel combustion, it becomes imperative to explore alternative energy solutions that can mitigate these impacts. The next section will examine optimisation strategies aimed at reducing emissions by integrating cleaner and more efficient energy sources.

7.3.5.2 Scenario analysis

Building on the base case assessment, two enhancement scenarios are evaluated to improve the enterprise's energy reliability and sustainability. Each scenario includes two sub-scenarios, differentiated by the choice of battery storage technology: lead-acid or lithium-ion. Since energy demand at both the production site and retail shop is predominantly electricity-based, the first enhancement focuses on replacing grid electricity with a solar PV system coupled with battery storage. Scenario 1, therefore, presents a practical and realistic solution, addressing key challenges such as grid unreliability, high fuel costs, and environmental concerns while ensuring a more stable and self-sufficient energy supply. Scenario 2 builds upon this foundation by eliminating LPG use for thermal demand at the production site and fully electrifying the enterprise with solar PV and battery storage. Since the required temperature for the process is only 50°C, this demand can be effectively met with electrical heating equipment, making the transition both technically feasible and cost-efficient. This shift enhances energy autonomy, reduces reliance on external fuel sources, and further minimises operational costs and environmental impact.

Scenario 1: Solar PV and battery storage to replace grid electricity while retaining LPG for thermal demand

While the thermal energy demand at the production site remains unchanged, with the entrepreneur continuing to use an LPG Bunsen burner for leather moulding, scenario 1 explores the replacement of grid electricity at both the

production site and retail shop with solar PV systems coupled with lead-acid battery storage (scenario 1A) and lithium-ion battery storage (scenario 1B). This transition aims to enhance energy reliability and mitigate environmental and operational drawbacks of backup petrol and diesel generators. Beyond the cost and emissions reductions achieved by eliminating fossil fuel use, this shift also reduces the operational disruptions caused by fuel scarcity, which occurs periodically in the country (Gad & Leone, 2025). Such shortages force employees to spend additional time securing fuel, often requiring them to travel longer distances to alternative fuel stations, leading to inefficiencies in business operations.

Net metering was initially explored as a potential enhancement strategy, offering a way for enterprises to feed surplus solar electricity back into the grid and offset overall energy costs. However, due to the absence of an operational regulatory framework and lack of immediate implementation plans, it was ultimately excluded from consideration in this case study (National Assembly of the Federal Republic of Nigeria, 2023; Okeke, 2023; Roux & Shanker, 2018).

Although Nigeria has made incremental progress in integrating renewable energy into its national agenda, the policy and infrastructure landscape remains insufficient to support small-scale net metering. The Electricity Act of 2023 introduced provisions for net metering (Sections 80 and 164), mandating the Nigerian Electricity Regulatory Commission (NERC) to issue implementation guidelines (National Assembly of the Federal Republic of Nigeria, 2023). Yet, no concrete framework or rollout plan has followed, leaving small producers without a pathway to sell excess power (NERC), 2015, 2016).

Beyond regulatory gaps, practical barriers further constrain implementation. The national grid remains ill-equipped to handle decentralised injections, burdened by ageing infrastructure, low metering rates (approximately 40%), and administrative inefficiencies (Dahunsi et al., 2021; Okeke, 2023; Vigotti et al., 2024). Crucially, the bidirectional smart metering system required for net metering remains largely unavailable or financially out of reach for most consumers.

Given these limitations, net metering cannot yet serve as a reliable mechanism for small-scale solar PV users in Nigeria. As such, alternative options for utilising surplus solar power, such as battery storage or direct on-site consumption optimisation, may be more practical in the near term. Scenario 1 is therefore structured around these more immediate, locally appropriate solutions, prioritising self-consumption and storage over grid export.

To develop scenario 1, several cost assumptions were required, based on data integrated into the HOMER Pro software. While literature highlights that solar PV CAPEX varies across different regions within Nigeria (Diemuodeke et al., 2021), the total CAPEX for a solar PV system was estimated by using country-specific data from ESMAP and comparing it with other scientific literature focused on Nigeria (Diemuodeke et al., 2021; ESMAP, 2022; IFC, 2021). The ESMAP dataset provides direct hardware costs for Nigeria while offering regional averages for the remaining cost components, based on data from Africa and Asia. The reported hardware cost for Nigeria is 477 USD/kW_p. According to ESMAP, on average, hardware accounts for 15.8% of the total mini-grid cost, with installation making up 16.8% and soft costs (such as permitting and project development) contributing 17.8%. Since only the hardware cost is provided, these proportions were used to extrapolate the total system cost. By scaling up the hardware cost accordingly and summing the relevant cost components, a total CAPEX of 1,507 USD/kW_p was estimated. This estimate aligns with other references. For instance, according to the (NERC, 2015) when computing a feed-in tariff for solar PV, its CAPEX is estimated at 1,500 USD/kW_p. Another study reports installation costs of 400 USD/kW_p, accounting for 23% of the total CAPEX (IFC, 2021). In this calculation, installation costs amount to 500 USD/kW, a slightly higher figure but still within a reasonable range, likely due to local variations in labour, logistics, and site conditions. Further supporting this calculation, another study provides estimated component costs: PV panels at 2.5 USD/W_p and a converter, which integrates the inverter and charge controller, at 0.30 USD/W_p (Diemuodeke et al., 2021). If these costs already include installation and soft costs, they would result in a total solar PV CAPEX of approximately 2,800 USD/kW, higher than the estimate using ESMAP data. However, ESMAP provides a structured, proportional breakdown of all cost components required to estimate CAPEX, ensuring a systematic and transparent approach, and is therefore used.

For battery costs, ESMAP provides values specifically for Nigeria, amounting to 180 USD/kWh and 331 USD/kWh for lead-acid and lithium-ion storage, respectively (ESMAP, 2022). Battery lifespan is commonly assessed based on energy throughput. Lead-acid batteries typically provide 800 kWh of throughput, with a maximum DoD of 60% and an efficiency of 80%, resulting in a total usable energy output of 384 kWh before requiring replacement. Conversely, lithium-ion batteries have a longer lifespan, offering approximately 3,000 kWh of throughput, with an 80% DoD and 90% efficiency, yielding 2,160 kWh of usable energy. However, real-world conditions, including operational and maintenance costs, ambient temperature, and cycling patterns, can further impact battery longevity

(Kebede et al., 2021; X. Zhang et al., 2021). To reflect these practical considerations, a conservative lifespan estimate of 5 years for lead-acid and 10 years for lithium-ion batteries is adopted, ensuring alignment with the literature while maintaining a realistic approach (Kebede et al., 2021; C. Zhang et al., 2017).

Based on these calculations, the most cost-effective technical configuration according to HOMER Pro involves a 20 kW_p solar PV system with 30 kWh lead-acid battery storage and a 5-kW inverter at the production site for scenario 1A. Meanwhile, the retail shop would be equipped with a 60 kW_p solar PV system, 50 kWh lithium-ion battery storage, and a 6-kW inverter to fully meet energy demands. Scenario 1B on the other hand requires only 10 kW_p solar PV system but with 40 kWh lithium-ion battery storage and a 5-kW inverter at the production site. At the retail shop, a 50 kWp solar PV system with 55 kWh lithium-ion battery storage and a 6-kW inverter is needed. As a result, petrol and diesel generators are no longer required. The finalised technical system layout is presented in Figure 49.

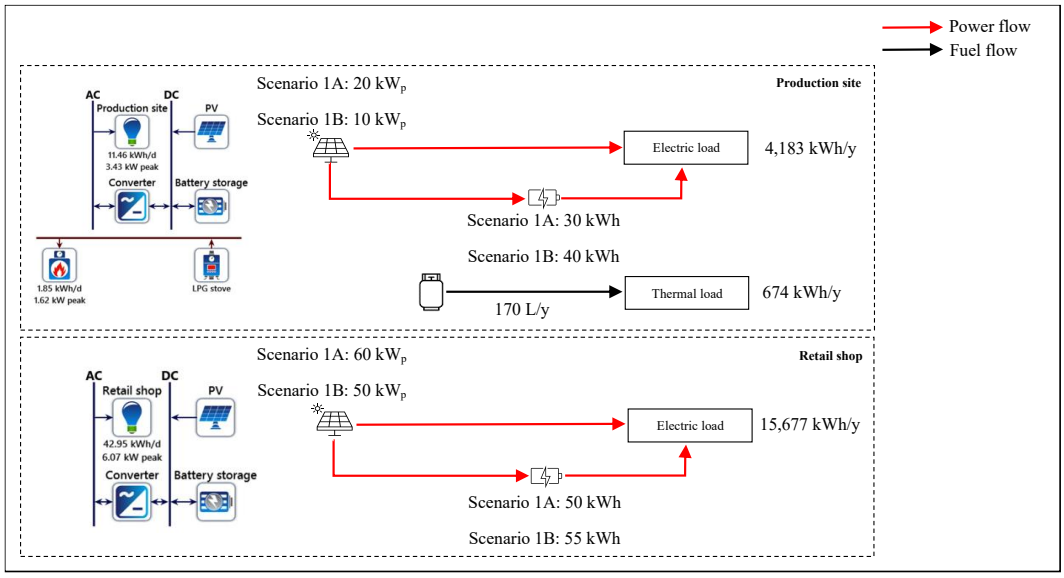

Figure 49. Case study 5: Technical setup of scenario 1

Notes: The left graphic was modelled with HOMER Pro, and the right graphic was modelled by the author. Scenario 1A contains lead-acid as battery storage, while scenario 1B contains lithium-ion battery storage

Abbreviations: kW = kilowatt; kWh/d = kilowatt-hour per day; kWh/y = kilowatt-hour per year; kW_p = kilowatt peak; LPG = liquified petroleum gas; L/y = litre per year; PV = photovoltaic

Across both locations and sub-scenarios, the solar PV and battery systems meet nearly all electricity demands, with only 0.04-0.09% of the load potentially unmet, still considered full energy coverage. The retail shop operates with a 100% renewable fraction, whereas at the production site, the renewable fraction reaches 86%, with the remaining 674 kWh/year for heating supplied by LPG. However, a substantial share of solar PV-generated electricity remains unused due to the lack of net metering or grid feed-in options. In scenario 1A, excess electricity accounts for 84% at the production site and 80% at the retail shop, while in scenario 1B, surplus generation is slightly lower, at 68% and 76%, respectively. Battery autonomy also varies between sub-scenarios. At the production site, the lead-acid battery in scenario 1A provides approximately 38 hours of backup power, whereas the lithium-ion battery in scenario 1B achieves 68 hours. At the retail shop, the lead-acid battery in scenario 1A allows for 17 hours of autonomy, compared to almost 25 hours in scenario 1B for lithium-ion battery storage.

Assuming the entrepreneur implements the shift to solar PV at both locations simultaneously, scenario 1 requires a substantial upfront investment but significantly reduces operating costs, an expected characteristic of renewable energy technologies like solar PV (Obada et al., 2024). While CAPEX is high, long-term O&M costs remain minimal. At a 6.86% discount rate over a 25-year project lifetime, scenario 1A leads to a 108% increase in NPC compared to the base case, though operating costs decrease by 50%. Scenario 1B performs slightly better, with an 86% NPC increase and a greater reduction in operating costs, achieving a 56% decrease relative to the base case. As anticipated, the initial investment in solar PV and battery storage constitutes the majority of NPC, accounting for 75% in scenario 1A and 77% in scenario 1B. The initially higher investment in lithium-ion batteries in scenario 1B is offset by their higher efficiency, longer lifespan, and reduced replacement frequency compared to lead-acid batteries. This results in lower long-term expenditures, further enhancing the economic viability in scenario 1B. Specifically, battery replacement costs, occurring every five years for lead-acid and ten years for lithium-ion, represent 9% of NPC in both sub-scenarios. Meanwhile, O&M costs for PV and battery systems remain minimal, and LPG fuel and Bunsen burner replacements contribute less than 1% of total costs. The salvage value of unused generators and inverters (which have a 15-year lifespan), as well as lithium-ion batteries in scenario 1B, provides a noteworthy NPC reduction of 3% in scenario 1A and 5% in scenario 1B.

Beyond the cost savings in annual operating expenses, the environmental impact reduction is also notable. Now limited to scope 1 emissions from LPG use

at the production site while the retail shop can be considered emission-free, the system results in 0.26 $tCO_{2\text{-}eq}$/year, representing a 98% reduction from the base case. In other words, under scenario 1, the enterprise can achieve a carbon footprint equivalent to 0.32 $tCO_{2\text{-}eq}$ per tonne of produced goods. This underscores the substantial potential of solar PV systems in replacing grid electricity and reducing carbon footprints.

Scenario 2: Full electrification with solar PV and battery storage, replacing both grid electricity and LPG

As opposed to scenario 1, where the thermal demand at the production site was met by an LPG burner, scenario 2 replaces this with an infrared heater. The remainder of the setup remains unchanged, meaning both the production site and the retail shop continue to rely entirely on solar PV coupled with battery storage, whereby scenario 2A utilises lead-acid and scenario 2B uses lithium-ion battery storage.

Various alternatives were considered to replace the LPG burner for leather moulding. The chosen solution needed to be simple to implement, closely resemble the existing process and remain cost-effective. Infrared and induction heating were among the viable options, as both technologies offer efficient heat transfer and can be adapted to different industrial applications (Aboud et al., 2019; Brown et al., 2016; Chen et al., 2004; Maznoy et al., 2020; Prist et al., 2017). However, infrared heating was ultimately selected due to its ability to provide direct radiant heat without requiring a metal mould or additional equipment, simplifying the transition while maintaining operational efficiency. Scientific studies have demonstrated that infrared heating achieves high thermal efficiency, with nearly all electrical energy converted into radiant heat, reducing thermal losses and improving energy use in industrial applications (Aboud et al., 2019; Brown et al., 2016; Maznoy et al., 2020).

To integrate infrared heating into scenario 2, the current thermal demand of approximately 56 kWh/month, when converting LPG to the final energy carrier, results in a requirement of 1.62 kW for two hours per day, four days per week. Considering an efficiency of 85%, an infrared heater with a power rating of at least 1.91 kW is needed to meet this demand. Although infrared heating is often considered nearly 100% efficient in terms of electric-to-heat conversion, the actual heat delivered to the intended target is lower and ranges between 39-85% according to various studies (Aboud et al., 2019; Brown et al., 2016; Maznoy et al., 2020).

The same time of use in the morning hours, between 9:00 and 10:00, is assumed, maintaining consistency with the base case and scenario 1 to avoid disruptions in the production schedule. While developing the setup for scenario 2, no readily available cost values for infrared heaters applicable to this specific case study were found in the literature. To ensure an appropriate system selection, three suppliers were contacted for quotations for a 2-kW infrared heater adequate for leather moulding. A response was received from Helios Quartz, which was used as the basis for this analysis. According to the supplier, the unit cost of a suitable infrared heater was estimated at 162 EUR (Helios Italquartz, 2025). However, after accounting for transportation, VAT, and all applicable taxes to deliver the equipment to the entrepreneur's location, the total cost was estimated at 845 USD. Additionally, no maintenance is required, as per the instruction sheet, and the emitter has a lifespan of 10,000 hours (Helios Quartz Group, 2025). Given an average usage of two hours per day during working days, this results in an operational life of approximately 19 years, necessitating only one replacement over the 25-year project period.

The adjustment in electrical supply made in scenario 2, increases the total electricity demand at the production site, combining the previous electrical load with the new thermal load, to 4,976 kWh per year. This represents an almost 17% increase in electric load demand compared to the base case. The addition of infrared heating results in higher peak demand during the morning hours, requiring a slight increase in the solar PV system, while battery storage remains equivalent to that of scenario 1. To accommodate this, the system is scaled up to 25 kW_p and 15 kW_p of solar PV in scenarios 2A and 2B, respectively. The final system setup is illustrated in Figure 50.

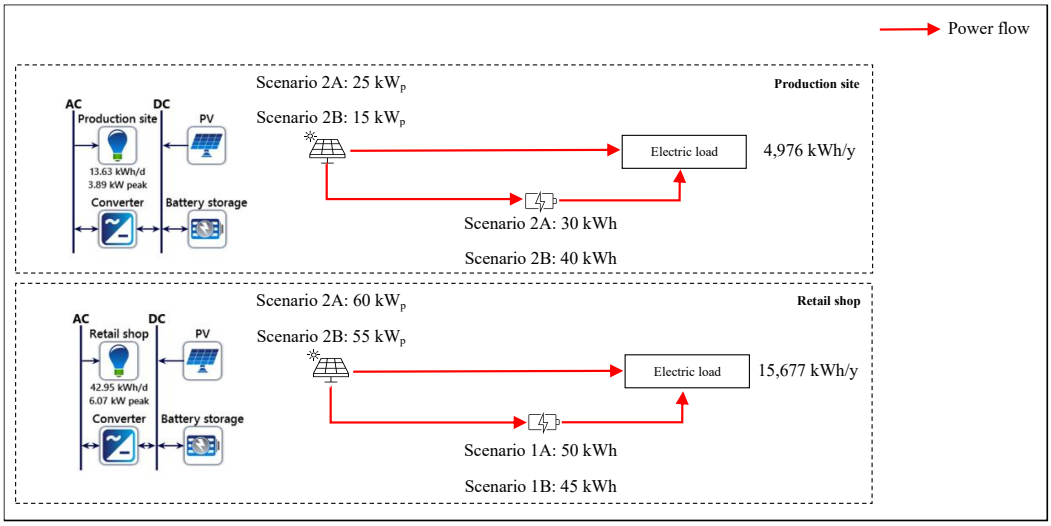

Figure 50. Case study 5: Technical setup of scenario 2

Notes: The left graphic was modelled with HOMER Pro, and the right graphic was modelled by the author. Scenario 2A contains lead-acid battery storage, while scenario 2B contains lithium-ion battery storage.

Abbreviations: kW = kilowatt; kWh/d = kilowatt-hour per day; kWh/y = kilowatt-hour per year; kW_p = kilowatt peak; PV = photovoltaic

Since the setup at the retail shop remains unchanged from scenario 1, it is not discussed further. With the transition to infrared heating at the production site, a 100% renewable energy fraction is now achieved. However, due to the lack of net metering or grid feed-in options, 85% and 75% of the solar PV-generated electricity is surplus and curtailed in scenarios 2A and 2B respectively. The 0.6% and 0.9% unmet demand in scenarios 2A and 2B respectively is negligible and does not indicate significant capacity shortages, similar to scenario 1. At the production site, the lead-acid battery in scenario 2A provides an estimated 32 hours of autonomy, while the lithium-ion battery achieves 56 hours of autonomy.

Scenario 2 requires a higher investment not only compared to the base case but also in relation to scenario 1. While operating costs remain similar to scenario 1, the NPC in scenario 2 exhibits a marginal increase of 5% and can be considered almost equivalent to that of scenario 1. At a 6.86% discount rate and over a 25-year project lifetime, the NPC in scenario 2A increases by 117% compared to the base case, whereas operating costs decrease by 50%. In scenario 2B, the NPC increases by only 95% and operating costs decrease by 57% compared to the base case, highlighting better economics for the lithium-ion scenario. As anticipated, the

initial investment in solar PV and battery storage constitutes the largest share of the NPC (77%), reflecting the system's capital-intensive nature. Meanwhile, battery and converter replacements account for 15% of the total NPC. Minimal O&M costs for the solar PV and battery system represent around 10-11%, highlighting the long-term economic benefits of a low-maintenance setup. The infrared heater investment, including necessary replacements due to its estimated 19-year lifespan, contributes less than 1% of the total NPC, further reinforcing its negligible financial impact over the project period.

Beyond the substantial cost savings in annual operating expenses compared to the base case, scenario 2 also delivers significant environmental benefits, as the system is now emission-free and fully autonomous. Eliminating reliance on external fuel sources not only mitigates exposure to price fluctuations and supply constraints but also aligns with long-term sustainability goals, ensuring a stable, clean, and independent energy supply.

Scenario analysis summary

The assessment was conducted for the enterprise's production site and retail shop, where the base case primarily relies on grid electricity supplemented by LPG for thermal demands, and two backup generators are used during grid outages. The challenges associated with this setup include limited availability and reliability of grid electricity, difficulties in sourcing backup fuel, and significant environmental burdens due to fossil fuel usage. Scenario 1 maintained the thermal energy demand at the production site, with the continued use of an LPG Bunsen burner for leather moulding. However, it introduced a transition to solar PV systems coupled with lead-acid and lithium-ion battery storage (scenarios 1A and 1B respectively) to replace grid electricity at both the production site and retail shop. This shift aims to enhance energy reliability and mitigate the environmental and operational drawbacks of backup petrol and diesel generators. Scenario 2 built upon scenario 1 by eliminating LPG use entirely and fully electrifying the enterprise, including the thermal demand at the production site. This results in complete energy autonomy through solar PV and battery storage, eliminating reliance on fuel and its price volatility.

As presented in Table 30, initial investment costs increase progressively from scenarios 1A to 2A and from 1B to 2B, with lithium-ion configurations (1B and 2B) consistently demonstrating superior cost efficiency over their lead-acid counterparts (1A and 2A) across initial investment, NPC, and operating costs.

Furthermore, operating costs between scenarios 1 and 2 remain comparable, with 1A and 2A, as well as 1B and 2B, exhibiting nearly identical values, though lithium-ion setups remain more cost-effective.

These findings yield two key insights: first, lithium-ion battery storage is the preferable option in this case study, as it results in lower initial investment, reduced NPC, and decreased operating costs. Second, the transition to a fully solar PV-powered system with battery storage does not impose a significant economic burden but instead enables full energy autonomy and a zero-emission production process. Over time, the reduction in fuel expenses, maintenance costs, and dependence on external energy sources could offset the higher initial CAPEX, making both scenarios financially and environmentally viable for long-term energy security and operational efficiency. Ultimately, the choice between configurations depends on funding availability, investment strategies, and sustainability objectives, particularly the priority placed on achieving complete energy independence and full decarbonisation.

Table 30. Case study 5: Comparison of initial investment, NPC, annual operating costs and GHG emissions for the base case and scenarios 1-2

	Initial investment	**NPC**	**Operating costs**	**GHG emissions**
Unit	USD	USD	USD/year	$tCO_{2\text{-}eq}$/year
Base case	0	85,800	7,300	14.84
Scenario 1A	134,900	178,200	3,700	0.26
Scenario 1B	121,800	159,200	3,200	0.26
Scenario 2A	143,300	186,100	3,600	0.00
Scenario 2B	130,200	167,100	3,100	0.00

Abbreviations: $tCO_{2\text{-}eq}$ = tonne of carbon dioxide equivalent; GHG = greenhouse gas; NPC = net present cost; USD = United States dollar

Looking ahead, further advancements in regulatory policies and infrastructure development in Nigeria could enhance the economic feasibility of solar PV adoption. If net metering regulations and grid modernisation efforts are implemented, the assessed enterprise could not only offset their own electricity costs but also generate additional revenue by selling excess electricity back to the grid. This would further reduce the NPC and improve financial returns, making the investment more attractive.

7.3.5.3 MTF evaluation

Applying the World Bank's MTF, this chapter evaluates the two enhancement scenarios for case study 5.

Several assumptions underpin this MTF assessment. Capacity requirements already achieved tier 5 in the base case and remain unchanged in scenario 1, with scenario 2 experiencing even a slight increase in electricity demand of approximately 17% due to the shift from LPG to electric heating. Availability assessments assume LPG remains fully available, as in the base case, and is assumed to fully meet thermal energy demands in scenario 1. Scenario 1 achieves high electrical availability, with unmet electrical loads ranging from just 0.04-0.08% at the production site and approximately 0.1% at the retail shop. Scenario 2, despite the slight increase in electrical demand, maintains similarly high availability, with unmet loads marginally increasing to 0.06-0.09% at the production site while remaining unchanged at 0.1% at the retail shop. The reliability metric reinforces these positive outcomes. At the production site, scenario 1 experiences minimal outages, ranging from 1-3 min/week. Scenario 2 records slightly higher weekly outages, between 2-3 min/week. At the retail shop, both scenarios experience outages of roughly 9-10 min/week. In terms of affordability, scenarios 1 and 2 both meet tier 5 criteria for electric supply, with costs at or below grid tariffs. However, the non-electric LPG supply in scenario 1 slightly exceeds grid tariffs, thereby achieving tier 4 affordability. Convenience assessments assign tier 5 performance for both electric and non-electric supplies, reflecting minimal operational disruptions. Health attributes are rated at tier 5 across scenarios, as both solar PV electricity and LPG are recognised as clean energy sources under MTF criteria. Safety conditions remain consistent with the base case, presenting no changes in risk assessment.

Figure 51 illustrates the incremental improvement in energy access tier performance for the Nigerian case study, assessed using the World Bank's MTF.

Initially, the base case performance is at tier 3, primarily constrained by availability, reliability, and convenience issues linked to grid outages and the reliance on backup generators. Notable improvements across both scenarios include substantially enhanced availability, reliability, and convenience of electric supply through the integration of solar PV systems. Although backup generators are not directly assessed under the MTF, their elimination notably improves convenience, addressing the entrepreneur's concerns regarding the physical effort and inconvenience of generator operations and associated fumes. Scenario 1 achieves an overall tier 4 score because non-electric supply via LPG remains slightly costlier than the grid tariff, restricting overall advancement. Scenario 2 achieves the highest possible performance, attaining tier 5 through complete electrification with solar PV and battery storage systems at both the production site and retail shop.

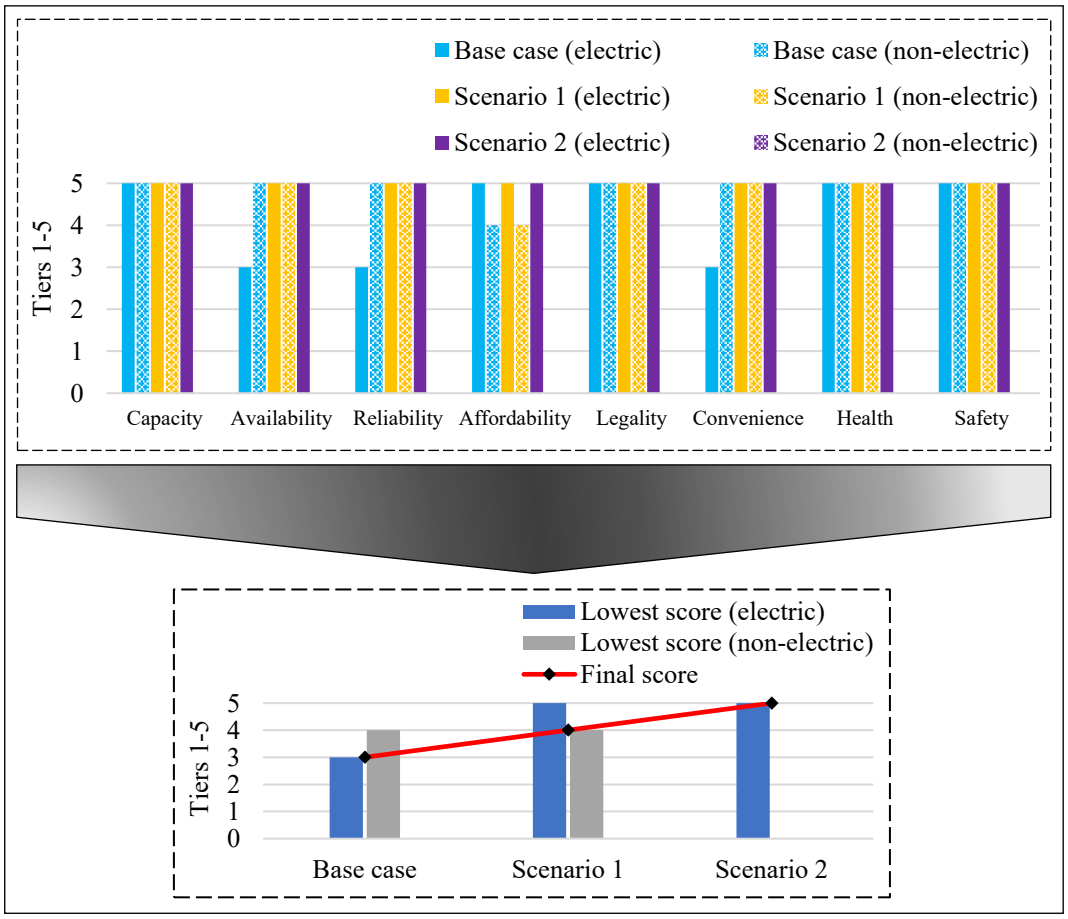

Figure 51. Case study 5: MTF tier performance comparison between base case and scenarios 1-2

Notes: Scenario 2 is fully electrified; therefore, the absence of an assessment for non-electric energy sources does not indicate a tier 0 rating but reflects that non-electric sources are not applicable in this scenario.

The analysis underscores the significant potential for improving operational efficiency, convenience, and overall sustainability through targeted energy solutions, especially the integration of solar PV and battery storage systems. Scenario 2 demonstrates optimal energy access performance achievable through complete electrification, effectively resolving key constraints faced in the base case. These outcomes illustrate how strategic investments in renewable energy technologies can substantially enhance enterprise productivity and operational comfort.

7.3.6 Case study 6: Tanzania – Textile manufacturing

To assess the potential for a community-driven energy access project aiming to support micro and small-scale enterprises within the batik manufacturing sector, it is necessary to begin with an examination of an entrepreneur from the dataset who developed this initiative (Gad & Leone, 2025). The study, therefore, opens with an assessment of a "reference entrepreneur", a well-established enterprise exemplifying productive energy use within the textile manufacturing industry. Her operations serve as the empirical baseline for modelling a community-driven energy access project in batik manufacturing, which she has initiated and actively supports. The reference entrepreneur's energy consumption patterns, operational practices, and institutional challenges form the foundation for developing assumptions about the energy needs and constraints of emerging women entrepreneurs in the same sector.

Located in Dar es Salaam, Tanzania, the reference entrepreneur runs a micro-sized, registered not-for-profit textile enterprise governed by a gender-diverse board in which the interviewed entrepreneur holds the majority shares (Gad & Leone, 2025). Specialising in the production of traditional Tanzanian fabrics, the organisation manufactures 200,000 fabric rolls/month, equivalent to around 42.8 tonnes of fabric/month (Tash, 2015). As a not-for-profit entity, it does not register a profit margin. Instead, income from fabric sales is reinvested into activities such as teaching women fabric manufacturing skills and raising awareness about cleaner manufacturing processes, including the use of LPG instead of charcoal and firewood. In addition, the operation generates 100 tonnes/day of dyeing wastewater, currently disposed of on-site.

Despite her success, the reference entrepreneur faces several structural and gender-specific challenges, including limited financing options, poor-quality cotton inputs, and sociopolitical resistance to her women-focused and clean-tech initiatives. Nevertheless, she is motivated to further decarbonise her production process and has expressed willingness to invest over 40,000 USD, along with a recurring monthly contribution of 700 USD, towards developing a biogas solution to further decarbonise the textile manufacturing sector, despite current technological and knowledge-related barriers.

This reference case provides critical insight into the energy conditions shaping the operational realities of the 50 aspiring women entrepreneurs featured in case study 6. Based on assumptions drawn from the reference entrepreneur's setup and contextualised through data from the scientific literature, the group's current energy access situation was assessed using the World Bank's MTF. The analysis yielded one of the lowest possible scores, tier 1, primarily reflecting the widespread reliance on traditional biomass fuels such as charcoal and firewood. These energy carriers are ranked at the lower end of the MTF due to their negative environmental footprint, high indoor air pollution risks, and limited suitability for modern productive use. The low tier score is further reinforced by the assumption that these fuels are frequently sourced through informal supply chains, which contributes to concerns around the legality of the energy carrier supply.

Building on this context, the following baseline assessment reconstructs the assumed energy system of this community-driven productive use initiative, detailing its technical setup, economic characteristics, and environmental implications. This baseline forms the analytical benchmark against which the relevance and potential impact of targeted energy enhancement scenarios will be assessed.

7.3.6.1 Base case

The reference entrepreneur's established practices and operational insights directly inform the modelling of a newly emerging, community-driven energy access project in batik manufacturing. This initiative supports 50 prospective women entrepreneurs in Dar es Salaam, each of whom is being mentored and equipped by the reference entrepreneur to establish micro and small-scale batik enterprises. While inspired by her model, their operations are in early development stages and reflect reduced production scales and constrained energy access conditions. That is why the community-driven energy access project assumes that

each of the 50 emerging women entrepreneurs operates at one-third of the energy demand of the reference entrepreneur due to their early-stage status.

The reference entrepreneur currently operates with tier 4 energy access of the World Bank MTF, largely driven by LPG use for thermal energy (899 kWh/month) and limited use of grid electricity (56 kWh/month) for ironing. Her productive use applications include boiling water, heating wax, and ironing. Frequent grid outages, averaging 4 hours per week, disrupt production, as the entrepreneur lacks any backup solutions to maintain operations during these downtimes. In contrast, for the community-driven energy access project, it is assumed that the thermal energy demand for boiling water and wax heating amounts to 300 kWh/month per entrepreneur, resulting in a combined demand of 15,000 kWh/month. Electricity consumption, primarily for one iron per entrepreneur, is estimated at 19 kWh/month per person, totalling 933 kWh/month for the group. The energy carrier assumptions reflect urban household consumption patterns in Dar es Salaam: 65% of households rely on biomass (6% firewood, 59% charcoal) and 35% use LPG (National Bureau of Statistics & Statistics Norway, 2023).

Applying these distributions, and as shown in Table 31, the group's estimated monthly thermal energy requirements translate into approximately 1,300 litres of LPG, 4,900 kg of charcoal, and 940 kg of firewood. For electricity, 87% of entrepreneurs are assumed to have grid access, consuming 812 kWh/month collectively. The remaining 13% are expected to use charcoal-powered irons, requiring approximately 67 kg/month or about 10 kg per entrepreneur.

Table 31. Case study 6: Summary of productive use applications

Process	**Temperature**	**Energy carrier**	**Appliance**		**Power rating or consumption**	
	°C	Type	Count	Type	Value	Unit
Boiling water	100	LPG; Charcoal; Firewood	50	stove	1,300; 4,902; 943	L/month; kg/month; kg/month
Heating, wax	60-80	LPG; Charcoal; Firewood	50	stove	2	kW

Ironing	110-180	Grid electricity	43	iron	2	kW
		Charcoal	7	iron	67	kg/month

Notes: LPG consumption is given in L/month, whereas charcoal and firewood consumption are provided in kg/month. The fuel consumption values represent the total energy consumption of a group of 50 women entrepreneurs.

Abbreviations: °C = degree Celsius; kg = kilogramme; kW = kilowatt; L = litre; LPG = liquified petroleum gas

To unpack the underlying assumptions in greater depth, the base case scenario for case study 6 draws on expected patterns of energy carrier use among the 50 women entrepreneurs. It assumes that the 50 women entrepreneurs initially rely on energy carriers commonly available in Dar es Salaam, such as LPG, firewood, charcoal, and grid electricity, reflecting typical energy use patterns of urban households in Dar es Salaam (Johnsen et al., 2015; National Bureau of Statistics & Statistics Norway, 2023). While the available data primarily captures domestic consumption, it is a reasonable foundation for estimating the energy carrier use likely to be replicated in the early stages of small-scale businesses. This assumption aligns with findings that Tanzania's batik industry operates largely within the informal sector, characterised by micro and small-scale businesses predominantly owned by women (Bigambo et al., 2024). Given the lack of specific data on productive energy use for enterprises of this type, it is further assumed that these women initially operate sole proprietorships with lower energy demands than the core entrepreneur. Each woman is assumed to require one-third of the thermal and electrical energy demand of the core entrepreneur, who employs two workers in addition to herself. Thermal energy demand is estimated at approximately 300 kWh/month per entrepreneur, primarily for boiling water and heating wax. For a group of 50 women, this corresponds to a total monthly thermal demand of nearly 15,000 kWh/month. The thermal load is assumed to follow a uniform daily profile, distributed evenly over a 10-hour working period from 5:00 to 15:00, based on interview data of the reference entrepreneur (Gad & Leone, 2025). In terms of electricity consumption, which is mainly associated with ironing, each entrepreneur is estimated to consume 19 kWh/month, yielding a collective demand of 933 kWh/month for the group. The assumed electrical load profile includes two 2-hour intervals per working day, one in the morning (7:00-9:00) and one around midday (11:00-13:00), reflecting observed usage schedules (Gad & Leone, 2025). All estimates are based on an operational calendar of 260 working days/year.

Delving deeper into the energy carriers used for meeting thermal demands, data from urban households in Dar es Salaam suggest that 65% of households rely on traditional biomass for thermal energy (National Bureau of Statistics & Statistics Norway, 2023). More specifically, 6% use firewood stoves, and 59% use charcoal. The remaining 35% are assumed to use LPG. These patterns reflect the widespread reliance on traditional biomass in urban Tanzanian households, making it reasonable to expect that women transitioning to entrepreneurship will initially adopt energy sources with which they are already familiar. Within the sample of 50 women entrepreneurs, the total thermal energy demand met by LPG is estimated at approximately 1,321 L/month. This calculation is based on an LHV of 47.3 MJ/kg, a density of 0.53 kg/L, and an appliance efficiency of 57% (Garg et al., 2006; Islam et al., 2022; Shen et al., 2018; Statistics Netherlands, 2025). For charcoal, the estimated monthly consumption is 4,902 kg/month, derived using an LHV of 29.5 MJ/kg and an appliance efficiency of 22% (Ekouedjen et al., 2020; Garg et al., 2006). Similarly, firewood consumption is projected at 943 kg/month, based on an LHV of 15.6 MJ/kg and the same efficiency of 22% (Ballard-Tremeer & Jawurek, 1996; Garg et al., 2006).

Electrical energy use is based on urban household electricity access rates, with 87%[16] of households in Dar es Salaam having access to grid electricity (National Bureau of Statistics & Statistics Norway, 2023). Accordingly, 87% of the women are estimated to collectively consume 812 kWh/month. For the 13% without electricity access, it is assumed that they will rely on charcoal-powered irons, with these 6 to 7 women consuming approximately 67 kg of charcoal per month or around 10 kg/person-month. This assumption aligns with sector data from the dataset (Gad & Leone, 2025). For example, a more established Kenyan entrepreneur in the wearing apparel sector, who uses a charcoal iron for her business with four employees, consumes approximately 120 kg of charcoal per month. Dividing this total among the five individuals results in an average consumption of 24 kg/person/month. By comparison, the lower figure assumed in this Tanzanian analysis reflects the early-stage nature of the businesses, where steam irons are likely to be used less frequently. Additionally, it accounts for differences in sectoral energy needs, as the wearing apparel sector typically requires more extensive ironing compared to the textile manufacturing sector (Gad & Leone, 2025).

[16] According to the World Bank Group et al. (2023), urban electrification rates in Tanzania are reported at 77%, though specific data for Dar es Salaam is not provided. Therefore, using national statistics is considered more appropriate for this context.

Figure 52 illustrates the technical setup, providing a summary of the electric and thermal demand and supply by energy carrier type, as shown in graphic c). Due to the limitations of HOMER Pro, as the software permits a maximum of two thermal loads and one thermal supply per simulation, the technical setup for each energy carrier was modelled first individually, and then the results from the simulations of each energy carrier were put together as indicated in graphic b). Additionally, graphic b) represents only electric ironing powered by grid electricity in its graphical visualisation, while the use of charcoal for ironing was incorporated into the thermal load associated with charcoal consumption.

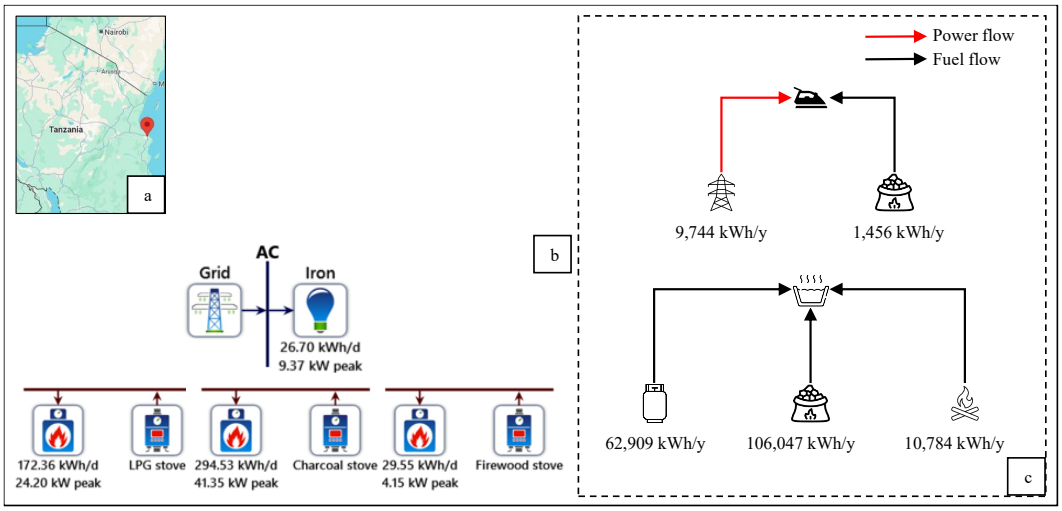

Figure 52. Case study 6: Technical setup of the base case

Notes: a) Geographic location, source: google.maps; b) Technical setup designed with HOMER Pro. Charcoal use for ironing is included in the thermal load graphic representing the charcoal demand and supply, while grid-powered ironing appears as an electrical load; c) Technical setup designed by the author.

Abbreviations: kW = kilowatt; kWh/d = kilowatt-hour per day; kWh/y = kilowatt-hour per year; LPG = liquified petroleum gas

The economic costs associated with these energy demands depend on the specific energy carriers used. Grid electricity costs are based on Tanzania's grid tariff of 0.1475 USD/kWh (EWURA, 2021). LPG costs are derived from the interview with the core entrepreneur used as a reference for assumptions made herein, estimated at 0.82 USD/L (Gad & Leone, 2025), which aligns with recent estimates from the Tanzanian Ministry of Energy, suggesting that LPG prices range between 0.64 USD/L and 0.86 USD/L (The United Republic of Tanzania & Ministry of Energy, 2024). Charcoal and firewood prices are more variable and

complex to estimate due to inconsistent measurement units (Inston & Scott, 2022; Norconsult Tanzania Limited, 2002). Based on a review of data sources, charcoal costs are set at 1,500 TSh/kg, approximately 0.62 USD/kg, while firewood is assumed to cost 185 TSh/kg, or approximately 0.077 USD/kg (Inston & Scott, 2022). These values align with high-end estimates from existing studies and are supported by national statistics (National Bureau of Statistics & Statistics Norway, 2023) and import price data (World Integrated Trade Solution (WITS), 2023). Beyond electricity and fuel costs, stove replacement is also accounted for, with an assumed replacement interval of 10 years (Mindjimba, 2020; Shaik et al., 2022). Estimated costs are set at 66 USD/unit for LPG stoves and 15 USD/unit for traditional or improved biomass cookstoves (Jeuland & Pattanayak, 2012; The United Republic of Tanzania & Ministry of Energy, 2024). Due to the lack of specific data on stove types in use, a conservative average is applied. While basic traditional stoves may cost under 10 USD and advanced models can reach up to 50 USD, a mid-range estimate of 15 USD is used to represent the likely average cost of non-LPG cookstoves (Jeuland & Pattanayak, 2012).

The analysis adopts a 25-year project lifetime and a 10% discount rate, which are commonly applied values for Tanzania in similar energy studies (Zigah et al., 2023), ensuring consistency across the different scenario analysis. Using these parameters and the assumed energy carrier costs, the base case projects a total NPC of 476,740 USD, with operating costs of 52,522 USD/year. Charcoal emerges as the most significant cost driver, representing almost 71% of total costs, followed by LPG at around 25%. Grid electricity and firewood contribute relatively modest shares, at less than 3% and 2%, respectively. Table 32 presents the cost breakdown by type of energy carrier.

Table 32. Case study 6: Net present cost and operating costs of the base case

Component	NPC (USD)	Operating costs (USD/year)	Share of NPC (%)
Energy carrier			
LPG	117,868	12,985	24.72
Charcoal	336,191	37,038	70.52

Firewood	7,866	867	1.65
Grid electricity	13,046	1,437	2.74
Replacements			
LPG stoves	619	68	0.13
Charcoal and firewood stoves	1,150	127	0.24
Total	**476,740**	**52,522**	**100%**

Notes: A nominal discount rate of 10% is applied, and the project lifetime is set for 25 years. Due to rounding, the sum of individual items may not exactly match the total.

Abbreviations: % = percent; LPG = liquified petroleum gas; NPC = net present cost; O&M = operation and maintenance; USD = United States dollar

In addition to economic and health-related concerns, the reliance on traditional biomass fuels raises substantial environmental implications. To quantify the associated GHG emissions, the environmental assessment for case study 6 applies the GHG Protocol and PCAF methodologies to estimate both direct (scope 1) and indirect (scope 2) emissions linked to current energy use practices (Gómez & Watterson, 2006; Greenhouse Gas Protocol, 2024; PCAF, 2020, 2022; UNFCC Secretariat, 2022).

The base case analysis estimates total emissions at 257.69 $tCO_{2\text{-eq}}$/year, resulting in a cumulative 6,442.25 $tCO_{2\text{-eq}}$ over the 25-year project lifetime. Assuming each of the 50 women entrepreneurs produces one-third of the core entrepreneur's output, this equates to 0.03 $tCO_{2\text{-eq}}$/tonne of goods produced. Nearly all (98%) of the emissions are from scope 1 fuels, with only 2% attributed to grid electricity use under scope 2. Within scope 1, the combustion of charcoal emerges as the dominant source of emissions, contributing a substantial 82%, while LPG use accounts for 10%, and firewood combustion contributes the remaining 8%.

These results underscore the significant environmental impacts associated with the reliance on traditional biomass fuels, emphasising the critical need for technological and operational improvements. Strategies to reduce GHG emissions,

improve efficiency, and enhance sustainability will be addressed in the subsequent sections.

7.3.6.2 Scenario analysis

This scenario analysis evaluates energy access solutions for 50 women entrepreneurs, who form part of a network centred around the core entrepreneur who was interviewed. Each scenario addresses specific energy challenges, with a focus on optimising energy use over a 25-year period. The energy consumption of the 50 entrepreneurs is assumed to be one-third that of the core entrepreneur. While it is acknowledged that energy demand may increase over time, the analysis limits calculations to a constant energy demand throughout the project lifetime. The base case and scenario 1 were modelled using HOMER Pro, however, for scenarios 2 and 3, additional calculations were required beyond HOMER Pro's scope, eliminating the need for modelling within the software.

As presented earlier, the base case assumes that the women entrepreneurs rely on common energy carriers available and used in Dar es Salaam. Scenario 1 explores a shift in energy use patterns, where all participants use grid electricity for ironing and LPG for heating water and wax. This scenario reflects the energy practices of the core entrepreneur, who has successfully integrated these energy carriers into her operations. Building on scenario 1, scenario 2 examines the use of biomethane derived from slaughterhouse wastewater to meet thermal energy demands. Electrical demand is still met via grid electricity. This scenario leverages an existing agreement with a slaughterhouse, where daily wastewater (7,000 litres from processing 100 cows and 60 goats) is available for biogas production. The biogas is upgraded to biomethane, then the produced biomethane is compressed and bottled for distribution to the entrepreneurs. Scenario 2 is further divided into three variations: 2A and 2B, where slaughterhouses rely on grid electricity for upgrading and compression but differ in the bottling pressure of biomethane (5-bar vs. 200-bar cylinders). In scenario 2C, a portion of the produced biomethane is used specifically to power the upgrading and compression processes, reducing reliance on external energy sources. Scenario 3 aims for full energy autonomy by eliminating reliance on the electrical grid. It investigates the feasibility of biogas production from municipal solid waste (MSW) using AD, a technology supported by the Tanzanian government. In this scenario, biodigesters are installed at each entrepreneur's facility, where MSW is collected from nearby households and processed to produce biogas for thermal and electrical energy needs.

Each scenario represents a distinct approach to addressing energy needs, from enhancing current energy practices with LPG and biomethane to achieving full energy independence with biogas production from waste. The following sections provide detailed insights into the techno-economic and environmental implications of each scenario.

Scenario 1: Grid electricity and LPG use

In transitioning from the base case to scenario 1, this analysis examines fuel switching for the 50 women entrepreneurs, focusing on techno-economic feasibility and environmental impact. This scenario assumes a shift in energy use patterns in which all participants would adopt electricity for ironing, replacing the current 13% who use charcoal for this purpose, and the remaining 65%, currently reliant on unsustainable biomass (charcoal and firewood), would transition to LPG (National Bureau of Statistics & Statistics Norway, 2023). These assumptions reflect the energy practices of the core entrepreneur, who has successfully integrated these energy carriers into her productive activities. It was further assumed that each entrepreneur would maintain one-third of the energy consumption of the core entrepreneur, serving as a reference.

While the analysis does not explore the broader behavioural and structural challenges of fuel switching, such as affordability, cultural preferences, and access to LPG, it is critical to note the inherent complexities of such transitions. Studies on fuel switching and fuel stacking often focus on cooking energy in the household or food production sectors (Foell et al., 2011; Masera et al., 2000; Mperejekumana et al., 2024; Nshimiyimana et al., 2024; Oyeniran et al., 2025; van der Kroon et al., 2013). In contrast, this case study examines fuel switching in the textile sector, specifically in small-scale batik manufacturing. Given the distinct energy requirements of textile production, some barriers commonly observed in the food sector, such as deeply ingrained cooking traditions or strong preferences for specific fuels, may not apply here (Mperejekumana et al., 2024; Oyeniran et al., 2025). Furthermore, the transition may be easier in this context due to the core entrepreneur's role as a key facilitator. Not only does she provide access to LPG through her existing distribution network, but she also trains and educates women entrepreneurs on the benefits and operational use of cleaner energy in textile manufacturing. The awareness and skills imparted through this initiative are likely to overcome some traditional barriers to fuel switching, fostering greater acceptance and adoption of LPG and electricity among the participants.

As shown in Figure 53, under this scenario, the total consumption for the 50 entrepreneurs would amount to 11,200 kWh/year of electricity and 45,283 litres of LPG per year, equivalent to 179,740 kWh/year.

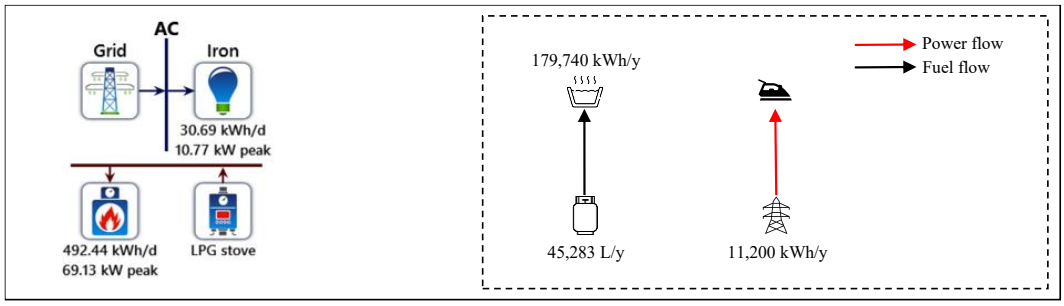

Figure 53. Case study 6: Technical setup of scenario 1

Abbreviations: kW = kilowatt; kWh/d = kilowatt-hour per day; kWh/y = kilowatt-hour per year; LPG = liquified petroleum gas; L/y = litres per year

Economically, scenario 1 requires relatively minimal initial investment, assuming charcoal and firewood stoves would be replaced with LPG-compatible stoves. According to the Tanzanian Ministry of Energy, the initial cost of purchasing a 15-kilogramme LPG cylinder is approximately 110,000 TSh, while a two-burner LPG stove costs around 50,000 TSh (The United Republic of Tanzania & Ministry of Energy, 2024). For comparison, a 6-kilogramme cylinder with its corresponding stove is estimated at 58,000 TSh. Since the Tanzanian Ministry of Energy explicitly provides the upfront cost of purchasing an LPG cylinder, a purchase model was assumed in this analysis rather than other LPG supply models (Perros et al., 2021; Shupler et al., 2024). For the productive use context, the combined initial investment for the stove and 15-kilogramme cylinder (which can be refilled afterwards) is considered to be 160,000 TSh, which is approximately 66 USD. This cost is notably lower than an estimate of 110 USD per stove, based on a 2017 study (Alem et al., 2017). Additionally, a connection charge is assumed for the 13% of currently off-grid women entrepreneurs, to connect them to the national grid. According to EWURA, the connection charge, including 18% VAT, varies depending on the distance to the service line (30, 70, or 120 meters) and whether the connection is in an urban or rural area (EWURA, 2021). For scenario 1, the urban connection cost was applied, and an average value was calculated based on the specified distances, resulting in an estimated 212 USD per connection.

Over a 25-year project lifetime at a 10% discount rate, the NPC would decrease by 25% compared to the base case, totalling 355,908 USD, with annual operating

costs of 37,321 USD/year, a drop of 29% compared to the base case. Most of these costs stem from LPG fuel expenses, which account for 95% of the NPC, followed by grid electricity costs, contributing another 4%. The initial investments in LPG stoves and the grid connection fee represent a minor 1% of the total NPC.

From an environmental perspective, the impact of scenario 1 is substantial. Annual GHG emissions would decrease by 71%, resulting in an annual emission of 75.77 $tCO_{2\text{-}eq}$/year, emphasising the significant environmental benefits of transitioning to cleaner energy carriers.

Scenario 2: Grid electricity and biomethane use from upgraded biogas produced through anaerobic digestion of slaughterhouse wastewater

Building on scenario 1, which addressed thermal heat demand through LPG while relying on grid electricity for electrical ironing, scenario 2 similarly evaluates how to satisfy thermal demand but instead assesses the techno-economic and environmental feasibility of biomethane derived from slaughterhouse wastewater as an alternative energy source. Electrical demand remains satisfied by grid electricity. This scenario was assessed because the entrepreneur has an existing agreement with one slaughterhouse and the potential to expand to additional facilities. The slaughterhouse generates on average 7,000 litres of wastewater daily from the processing of 100 cows and 60 goats, which is available at no cost (Gad & Leone, 2025). Currently, the lack of enforcement of waste regulations leads to wastewater being disposed of in open areas, creating an environmental challenge but also offering the potential for resource recovery via biogas and biomethane production (EWURA, 2019, 2020; Michael et al., 2020).

In scenario 2, it is assumed that the biogas produced from slaughterhouse wastewater is first stored in an intermediate storage tank before being upgraded and compressed into biomethane, which is then bottled and transported to collection points near the women entrepreneurs. Within this general setup, scenario 2 is further divided into three variations: Scenarios 2A and 2B assume that slaughterhouses rely on grid electricity for upgrading and compression. The key difference between them is that scenario 2A considers bottling the biomethane in 8-bar cylinders, while scenario 2B assumes bottling in 200-bar cylinders. Scenario 2C, on the other hand, explores the feasibility of using a portion of the produced biomethane to meet the slaughterhouse's own electricity demand for upgrading and compression, thereby reducing the net biomethane available for distribution. The remaining biomethane is then bottled in 200-bar cylinders. To assess the techno-economic feasibility of

scenario 2, a series of parameters and assumptions were required, which are summarised and presented in Appendix D.

The wastewater treatment unit in this study is simplified to an AD system. The focus was placed on AD without delving into the specifics of pre-treatment processes or existing wastewater treatment technologies (Silva, 2023). The basis for estimating the biogas production potential is grounded in using the chemical oxygen demand (COD) and its ability to quantify the organic matter in wastewater that can be biologically degraded to produce methane. COD is a standard parameter in AD modelling due to its correlation with the organic substrate available for microbial activity. This makes it a reliable metric for predicting biogas yields across diverse wastewater compositions. Studies like Bhunia et al. (2022), Martí-Herrero et al. (2018), and Otero et al. (2021) validate the use of COD in estimating methane yields with COD removal efficiency, providing an estimate of the degradable fraction. To estimate biogas production through AD, the COD of the wastewater was based on literature for similar contexts, assuming a concentration of 4,400 milligrammes per litre (mg/L) (Bhunia et al., 2022). COD concentrations in slaughterhouse wastewater can range widely, from as low as 4,000 mg/L to as high as 18,000 mg/L, depending on the type of wastewater and treatment practices (Bhunia et al., 2022; Michael et al., 2020; Yazdani et al., 2019). The methane yield per kilogramme of COD was set at 0.36 m^3/kg COD (Martí-Herrero et al., 2018), comparable to 0.35 m^3/kg (Jørgensen, 2009), and still within a reasonable range when compared to lower values of 0.29-0.32 m^3/kg COD and 0.22-0.26 m^3/kg COD as reported in other studies (Díaz, 2015; Otero et al., 2021). A COD removal efficiency of 77.8% and a methane content of biogas of 55.05% were assumed, derived as the average from reported values by Martí-Herrero et al. (2018). This latter value aligns with commonly observed methane contents in biogas produced from organic wastewater (Ware & Power, 2016).

It is assumed that the system operates on a 10-day cycle, during which biogas is continuously produced at a rate of 15.67 m^3/day and stored in an intermediate storage tank. Based on the input feedstock and an assumed hydraulic retention time (HRT) of approximately 25 days, a commonly reported value in the literature for similar AD systems (Martí-Herrero et al., 2018), the required AD system capacity is estimated at around 170 m^3 (Sasse, 1988). Once the tank is full, the entire 156.7 m^3 of stored biogas undergoes upgrading. Although raw biogas could be directly utilised in biogas stoves or generators for electricity production (Kabeyi & Olanrewaju, 2022; Mohanty et al., 2016; Nallamothu et al., 2013), scenario 2 involved upgrading the biogas to biomethane using water-scrubbing technology

which includes compression to up to 8 bar (Budzianowski et al., 2017). While various technologies are available for biogas upgrading, water scrubbing was selected due to its technical maturity, wide use, and lower technical complexity (Ahmed et al., 2021; Bauer et al., 2013; Benizri et al., 2019; Kapoor et al., 2017; Kvist & Aryal, 2019; Nock et al., 2014). The upgrading process removes CO_2 and other impurities by dissolving them in water, requiring a continuous water input and generating wastewater as a byproduct. Although this introduces potential logistical challenges related to water supply and waste management, it enables effective methane purification without the need for chemical solvents or complex separation systems. For calculation purposes, the methane concentration of the obtained biomethane was assumed to be 100%, though, in practice, it typically ranges from 90% to 98% (Ahmed et al., 2021; Benizri et al., 2019; Kabeyi & Olanrewaju, 2022; Krich et al., 2005; Nock et al., 2014). Upgrading incurs a higher cost compared to the direct use of biogas, which requires only minimal treatment for thermal or electrical applications, but the purification process optimises the gas for long-term storage and ease of transport to the collection points, ensuring a higher-quality, more efficient fuel source (Ahmed et al., 2021; Bauer et al., 2013; Kabeyi & Olanrewaju, 2022; Krich et al., 2005).

After each 10-day cycle, approximately 84.57 m^3 of biomethane exits the upgrading unit, accounting for a 1.97% methane loss during the upgrading process (Cappannelli et al., 2020; Gómez & Watterson, 2006; Kvist & Aryal, 2019; Nock et al., 2014). Methane losses in water scrubbing units are common and typically range between 1-2% (Bauer et al., 2013), with some systems reporting losses as high as 3-5% of the total methane content in biogas (Kapoor et al., 2017). Biomethane was assumed to behave as an ideal gas at Normal Temperature and Pressure (NTP), with its density remaining constant, which results in numerically equivalent mass-based and volume-based loss calculations. The three different sub-scenarios vary in how the biomethane is handled afterwards: In scenario 2A, the upgraded biomethane is directly bottled in cylinders, as it already has a pressure of approximately 8 bar, with only minor pressure differences that are not considered herein (Budzianowski et al., 2017). In scenario 2B, the upgraded biomethane is sent to a second compressor for further compression to 200 bar before bottling in cylinders. In both scenarios, 2A and 2B, the electrical demand, upgrading only in 2A (approximately 36 kWh/10-day cycle), and both upgrading and second compression for storage in 2B (approximately 52 kWh/10-day cycle), is supplied by the grid. The estimated electrical energy demand of 0.23 kWh/m^3 biogas entering the upgrading and 0.19 kWh/m^3 of biomethane entering the second compression unit is in line with typical values for similar technologies (Bauer et al.,

2013; Budzianowski et al., 2017; Nock et al., 2014). In scenario 2C, however, the upgraded biomethane is used to generate electricity to meet the energy needs of both the upgrading unit and the second compression required for bottling in cylinders. To supply this energy demand in scenario 2C, a generator with 35% efficiency is assumed (Ciuła et al., 2022). The generator consumes 14.2 m^3 of biomethane per cycle, producing 50 kWh of electricity, with a power output of around 6 kW during its 8-hour daily operation. The generator's fuel consumption rate is 0.2860 m^3 of biomethane per kWh generated. The remaining 70.4 m^3 of biomethane are directed to the second compressor for bottling.

To meet the thermal energy demand of the beneficiaries, it was determined that biogas from approximately 8 to 10 slaughterhouses would be required. The mathematically calculated values suggest 8.17 slaughterhouses for scenarios 2A and 2B, and 9.60 slaughterhouses for scenario 2C. This necessitates a decision of either rounding up to 9 and 10 slaughterhouses, respectively, which would result in excess production and potentially increased costs, or rounding down to 8 and 9 slaughterhouses, which may fall short of meeting demand. To make 8 slaughterhouses feasible for scenarios 2A and 2B, adjustments such as increasing wastewater influx by at least 100 L/day could be considered. Similarly, for scenario 2C, an increase of at least 400 L/day would be required to meet demand with only 9 slaughterhouses. This analysis follows the mathematically calculated values, which, while not directly reflecting real-world constraints, serve as the foundation for the techno-economic model.

To estimate the logistics of bottling biomethane in cylinders, loading them onto a truck, and transporting them to the end-users, the number of cylinders required was calculated based on the filling capacity of available cylinders at 8 bar and 200 bar pressure. For this, average cylinder capacities were used, with 8 bar cylinders assumed to have a volume of approximately 30 litres and a tare weight of 22 kg, while 200 bar cylinders were estimated at 44 litres with a tare weight of 84 kg (Mathesongas, n.d.). The assumption for low-pressure storage (8 bar) was that similar cylinders to those used for LPG could be utilised, whereas, for high-pressure storage (200 bar), steel or alloy cylinders would be required. The density of biomethane was then determined for both pressure levels using the ideal gas law[17],

[17] The density of biomethane at different pressures was calculated using the ideal gas law, expressed as $PV = nRT$ and density $\rho = (M \times P) / (R \times T)$ (Atkins & de Paula, 2006). In these equations, P represents pressure (Pa), V is volume (m^3), n is the number of moles of gas, R is the universal gas constant (8.314 J/mol-K), and T is the absolute temperature (K). The molecular weight of methane (M) was assumed 16 g/mol or 0.01604 kg/mol. For the calculations, a standard

while acknowledging that deviations from ideal gas behaviour at higher pressures may introduce errors in the estimation (Atkins & de Paula, 2006). At normal conditions, biomethane was estimated to have a density of approximately 0.65 kg/m^3, which is similar to existing values found in the literature (Dutt, 2003). The density increases to around 5.17 kg/m^3 at a pressure of 8 bar and to 129.16 kg/m^3 at a pressure of 200 bar. In scenarios 2A and 2B, the produced biomethane available for bottling is equivalent to 5.46 kg/day. In scenario 2C, this amount is reduced to 4.65 kg/day available for distribution. Consequently, scenario 2A results in filling around 358 cylinders per 10-day cycle per slaughterhouse, while in 2B and 2C, the number of cylinders filled is significantly lower, with fewer than 10 and around 8 cylinders per 10-day cycle, respectively. All sub-scenarios assume a truck with an 8-tonne weight capacity, which moves after each 10-day cycle. However, there are some key distinctions between the sub-scenarios. In Scenario 2A, it is assumed that each slaughterhouse has a dedicated truck for distribution. After each 10-day cycle, this truck transports 358 cylinders, with a total weight of approximately 8 tonnes, to the beneficiaries. This means that around seven cylinders are distributed to each female entrepreneur, providing enough supply for a 10-day period before the next shipment arrives. In scenarios 2B and 2C, only one truck operates every 10 days, collecting cylinders from all slaughterhouses. This results in the collection and distribution of approximately 80 cylinders, with a total weight slightly below the truck's 8-tonne capacity. Each entrepreneur, on average, would require just under two cylinders for a 10-day period. At this stage of the analysis, no further detailed logistical arrangements have been made. It is assumed that the cylinders required for each cycle are those already in use, which will be recollected, refilled, and redistributed in preparation for the next cycle. The main technical setup of scenario 2, with its divisions ranging from 2A to 2C is presented in Figure 54.

temperature of 298 K (25°C) was assumed. The density was determined for pressures of 8 bar (800,000 Pa) and 200 bar (20,000,000 Pa), recognising that deviations from the ideal gas law may introduce errors, particularly at higher pressures.

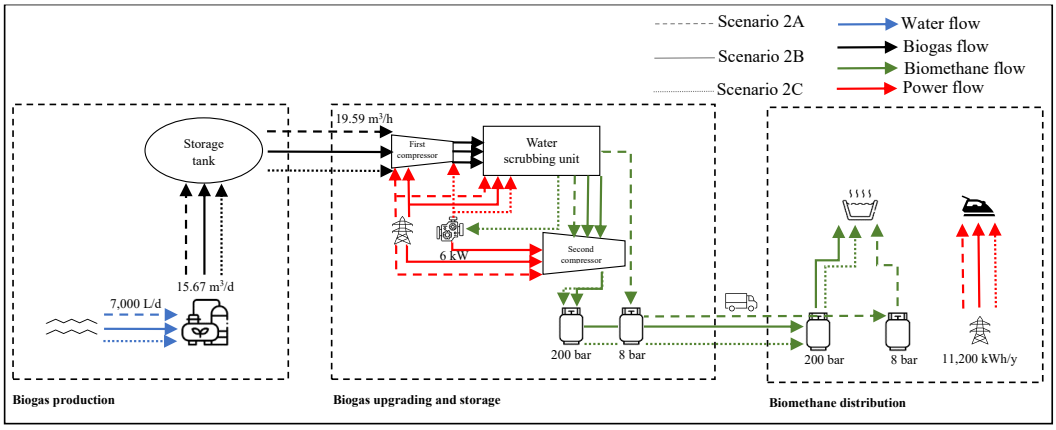

Figure 54. Case study 6: Technical setup of scenario 2

Notes: It is assumed that the first compressor consumes 0.13 kWh/m³ of biogas entering the unit, while the second compressor consumes 0.19 kWh/m³ of biomethane entering the unit (Bauer et al., 2013; Noussan et al., 2024).

Abbreviations: kW = kilowatt; kWh/y = kilowatt-hour per year; L/d = litre per day; m³/d = cubic meter per day; m³/h = cubic meter per hour

The costs of biogas production, upgrading, and compression were based on literature data. The costs of an AD system are influenced by several factors, including the specific technologies used, the processing methods involved, and the type of waste being treated. While the Ministry of Energy of Tanzania reports values as low as 108 USD/m^3 of AD capacity (The United Republic of Tanzania & Ministry of Energy, 2024), other studies indicate costs reaching up to 202 USD/m^3 of AD capacity (Amigun & von Blottnitz, 2010). For this study, costs were assumed based on values provided by local developers in Tanzania, where the AD system is priced at 186 USD/m^3 of AD capacity. This cost includes installation and a five-year warranty period, with no O&M costs assumed during this period (Energy and Environment Partnership, 2019). From year six onwards, O&M costs were assumed to account for 15 USD/year. Estimating the costs associated with upgrading and compression proved challenging due to their high variability depending on the technology used, local context, and biogas flow rate. The cost of water scrubbing technology is estimated at an average cost of 2,175 USD per cubic meter per hour (m^3/h) based on literature values (Suliman, 2022). This falls within the broader range of 1,500 to 5,000 USD per m^3/h reported in other studies, though these figures are often derived from higher flow rates (Bauer et al., 2013). The initial investment for the compressor in both scenarios 2B and 2C is estimated at 27,048 USD, based on a base cost of 19,600 USD from market prices (Alibaba.com, 2025a), with an additional 18% VAT (PwC, 2025), 10% transportation cost, and 10% contingency.

The CAPEX of compressors reported by Apt et al., (2008) span from 650 USD/kW for industrial-sized compressors to 6,600 USD/kW for smaller-sized compressors which would be more applicable for this case. Another study focuses on flow rates and suggests a comparable cost of approximately 25,000 USD/compressor, based on scaling factors from a plant processing 189.4 m^3/h (Ferrari et al., 2024). Minimal differences in flow rate and capacity between scenarios 2B and 2C are not accounted for because the compressors used in these scenarios are relatively small, and the variations in size and performance are assumed to be not significant enough to impact the cost estimate at this scale. Annual O&M costs for upgrading and compression for storage were assumed to be 2-3% of the initial CAPEX (Bauer et al., 2013). Additionally, for scenario 2C, an extra CAPEX of 600 USD per kilowatt (kW) of generator capacity was considered, with an operational cost assumption of 0.03 USD/kW/operating hour as is in line with default values set by HOMER Pro. Moreover, no generator replacement costs are considered as the generator is assumed to operate for a total of 20,000 hours before needing replacement. With an operational schedule of 8 hours every 10 days over 260 days per year, the generator's lifetime exceeds the project lifetime, meaning no replacement costs are anticipated within the project timeframe.

Grid electricity costs are derived from the established grid tariff of 0.1475 USD/kWh (EWURA, 2021). In scenarios 2A and 2B, the total grid electricity demand was calculated to cover both biogas processing at the slaughterhouses and the energy needs of the beneficiaries. In scenario 2A, where only upgrading is required, the total annual electricity demand amounts to 18,860 kWh/year. In scenario 2B, this demand is slightly higher at 20,837 kWh/year due to the additional electricity required for biomethane compression for storage in cylinders. In scenario 2C, however, only the grid electricity demand of the beneficiaries, 11,200 kWh/year, was considered, as the energy required for biogas upgrading and biomethane compression is fully supplied by an on-site generator. Additionally, grid access costs were factored into the analysis, with 13% of slaughterhouses and beneficiaries in scenarios 2A and 2B assumed to incur a one-time connection fee for grid access (National Bureau of Statistics & Statistics Norway, 2023). In scenario 2C, this cost applies only to the beneficiaries.

Transportation and logistics costs needed to be considered as well, given the varying distances between beneficiaries, which range from 5 to 50 km from the slaughterhouses. It was assumed that each truck covers a maximum round-trip distance of 100 km. Fuel consumption for diesel trucks, based on values for similar vehicles used in Kenya, was estimated at 0.01327 L/tonne-km (Abiero et al., 2015),

with diesel prices set at 1.24 USD/L (EPRA, 2023). Additionally, driver wages were estimated at around 17-18 USD/trip, based on reported salary data for Tanzania (Mywage.org/Tanzania, 2025).

Finally, it was assumed that beneficiaries would require biogas stoves for end-use. These were considered to cost 66 USD each, comparable to the costs of LPG stoves (The United Republic of Tanzania & Ministry of Energy, 2024). The assumption was made, that these biogas stoves require replacement every 10 years (Mindjimba, 2020; Shaik et al., 2022).

From an economic perspective, with a 10% discount rate and a 25-year project lifetime, the NPC and operating costs increase progressively from scenario 2A to 2B to 2C. Compared to the base case, all sub-scenarios within scenario 2 result in higher NPCs but achieve a significant reduction in operating costs, ranging from 62-65%, depending on the sub-scenario. Scenario 2A has the lowest NPC among the three, representing a 66% increase compared to the base case, with annual operating costs of 18,148 USD/year, a 65% reduction from the base case. In contrast, scenario 2B incurs a significantly higher NPC due to the additional compression step, reaching a 112% rise compared to the base case, while operating costs amount to 18,578 USD/year. The NPC in 2C results in a 157% increase compared to the base case, with annual operating costs of 19,820 USD/year. In all sub-scenarios, the CAPEX for the total technical setup, particularly the upgrading and compression units, constitutes the largest share of the NPC, accounting for 79% in scenario 2A and approximately 83% to 85% in scenarios 2B and 2C, respectively. In scenario 2A, the remaining costs mainly stem from the O&M of the AD and upgrading units (10% of NPC), followed by transportation and distribution costs (7% of NPC). Other expenses, such as grid electricity and biogas stoves, contribute to a minor extent. In scenarios 2B and 2C, the compression unit leads to relatively higher costs, which do not offset the economic benefits of compressing biomethane at a higher pressure to reduce transportation frequency. Additionally, in scenario 2C, costs exceed those of scenario 2B due to the investment in generators for on-site electricity generation at the slaughterhouses, which do not offset the costs associated with grid electricity use.

The environmental impact assessment of GHG emissions was conducted across scope 2 (indirect emissions from electricity use) and scope 3 (emissions from transportation) in accordance with methodologies established by the GHG Protocol, IPCC, and PCAF (Gómez & Watterson, 2006; Greenhouse Gas Protocol, 2024; PCAF, 2020, 2022; UNFCC Secretariat, 2022). Moreover, methane emissions from

an estimated 1.97% loss during biogas upgrading, which are released into the atmosphere, were accounted for due to their substantial contribution to overall emissions. These emissions are estimated at 5-6 $tCO_{2\text{-}eq}$/year, representing 30-53% of total GHG emissions within this scenario, assuming a GWP of 27 (Greenhouse Gas Protocol, 2024). Variations in emissions within scenario 2 primarily result from scope 2 emissions associated with grid electricity use and scope 3 emissions related to transportation, leading to differences in total GHG emissions across sub-scenarios. Scenario 2C exhibits the lowest GHG emissions at 12.19 $tCO_{2\text{-}eq}$/year, followed by scenario 2B at 15.72 $tCO_{2\text{-}eq}$year, while scenario 2A shows slightly higher emissions at 18 $tCO_{2\text{-}eq}$/year. Compared to the base case, scenarios 2A and 2B achieve a reduction in GHG emissions of approximately 93% and 94%, respectively, while scenario 2C achieves a 96% reduction. These findings highlight the significant mitigation potential of biomethane in reducing overall emissions.

Scenario 3: Achieving energy autonomy through biogas use from anaerobic digestion of municipal solid waste

Scenario 3 was developed to achieve full energy autonomy for the 50 women entrepreneurs in the Tanzanian case study, eliminating reliance on the electrical grid, as was the case in the enhanced scenarios 1 and 2. This scenario explores the feasibility of biogas production and utilisation from MSW using AD. The approach was chosen for two primary reasons: the Tanzanian government's support for domestic biodigesters, which has led to their development and distribution across the country (Amigun & von Blottnitz, 2010; Ng'wandu et al., 2009), and the significant waste management challenges that the country faces (Mbuligwe & Kassenga, 2004; Razafinirinamaharavo, 2021; United Nations Human Settlements Programme (UN-Habitat), 2021). Given these two factors, the potential for scaling up the relatively mature AD technology in the country warranted further investigation.

Scenario 3 envisions the installation of local AD at each woman entrepreneur's home or textile manufacturing facility, facilitating decentralised energy production directly at the point of demand. MSW is collected from surrounding areas and transported to each entrepreneur's location, where it undergoes AD to produce biogas. This biogas is then stored in an intermediate tank, from which it is sent to a biogas cleaning unit to remove hydrogen sulphide (H_2S) and other impurities, ensuring it meets the required quality for use. The processed biogas is then directed into biogas stoves to provide thermal energy for heating needs. Additionally, the cleaned biogas is channelled into a generator, which supplies electricity to power

the facility's essential operations, including the biogas cleaning process, as well as meeting the electrical demand for ironing, a key component of the productive use needs of the entrepreneurs. The modelling of this scenario required several key assumptions, detailed in Appendix D. It should be noted that CHP is not considered in this system due to the significantly higher thermal demand compared to electrical demand, making its implementation inefficient (Thorin et al., 2015). CHP systems are designed to simultaneously produce both electricity and heat, operating most efficiently when these outputs are required in relatively balanced proportions. When heat demand far exceeds electricity demand, the CHP unit would either produce excess electricity that may go unused or it would fail to meet the full thermal demand, requiring additional heating solutions. This leads to higher costs and lower overall efficiency. In cases where thermal demand dominates and electricity needs are minimal, as is the case presented herein, dedicated heating solutions with direct biogas combustion are often more cost-effective.

The estimation of biogas requirements for each of the 50 systems encompasses both thermal and electrical energy demands, including those for productive activities and the operation of the H_2S removal unit[18]. The thermal energy demand is approximately 13.83 kWh/day, while the electrical energy demand for ironing amounts to 0.86 kWh/day. With a biogas energy content of 6.11 kWh/m^3 (Cappannelli et al., 2020), this translates to 2.26 m^3/day needed for heating applications using dedicated biogas stoves, and 0.47 m^3/day to power irons, assuming a generator electrical efficiency of 30% (Ciuła et al., 2022; Kabeyi & Olanrewaju, 2022). To ensure that the generator could meet peak demand for the irons, which require 2 kW of power (Gad & Leone, 2025), a 20% contingency was added, resulting in a required generator capacity of 2.4 kW.

Determining the energy consumption of the biogas cleaning unit presents a challenge, particularly for small-scale systems, as most available literature provides energy consumption values for larger flow rates (Allegue & Hinge, 2014; Choudhury et al., 2019). To estimate the energy demand for biogas cleaning, a reference case with a significantly higher flow rate of 200 m^3/h is used, where 9,000 kWh/year is consumed for gas treatment over 8,500 hours/year (Allegue & Hinge,

[18] It is acknowledged that household energy consumption may also require modelling or could serve as an additional avenue for investigation, particularly in cases where AD units are integrated at the entrepreneur's residence. However, as the primary focus of this study is on productive energy use, household energy demands fall outside the scope of this analysis.

2014). Assuming a linear relationship between flow rate and energy consumption, the specific energy demand for H_2S removal is 0.0053 kWh/m^3 of biogas treated[19].

In this study, the daily biogas production rate is determined based on meeting the total system's daily energy demand. While an intermittent storage period of approximately 7 days is considered for practical purposes of biogas cleaning, it is assumed that this storage does not interfere with the ability to meet the daily productive use demand. Biogas was assumed to accumulate until a volume of 20 m^3 is reached, allowing purification in a single one-hour cleaning cycle at 20 m^3/h. The total energy required for this cleaning process is 0.106 kWh per cycle, representing a minimal but necessary electrical demand for the system. Using the same 2.4 kW generator that powers the iron, an additional 0.0079 m^3/day of biogas is required to operate the H_2S removal unit. Consequently, the total daily biogas production rate, satisfying the productive use activities (thermal and electric demand) as well as the energy demand required for on-site biogas cleaning, is estimated at 2.73 m^3/day.

To estimate the required waste input accordingly, food waste was considered the primary feedstock, with a biogas yield of 0.092 m^3/kg of fresh matter (FM), representing waste with a medium fat content (Bayerische Landesanstalt für Landwirtschaft (LfL), n.d.). Alternative approaches estimate biogas yields and biomethane potential based on the volatile solids (VS) content of the feedstock, as biogas production is directly proportional to the amount of VS present (Bhave & Patil, 2022; Elango et al., 2007; Rao et al., 2000; Sedighi et al., 2022). The FM-based assumption was considered reasonable given the limited availability of data on VS and total solids (TS) composition, and it aligns with values reported in the literature. The calculation resulted in a requirement of almost 30 kg of FM/day/AD unit. Using national statistics on food waste generation in Tanzania, it was determined that approximately 24-25 households, each producing an average of 1.225 kg of food waste daily, would be needed to supply one AD (UN-Habitat, 2021; The United Republic of Tanzania et al., 2022).

To assess the logistics of waste collection, the population density of Dar es Salaam was used to estimate the distance that a collection truck would need to travel (The United Republic of Tanzania et al., 2022). The assumption was that a single

[19] Uncertainties and limitations in estimating energy consumption for biogas cleaning in small-scale systems are acknowledged as extrapolation from larger-scale references assumes proportionality, which may not fully capture scaling inefficiencies and system-specific variations.

truck would collect food waste from participating households every two weeks and transport it to the AD. The collected and transported food waste amounts to approximately 418 kg/2-week cycle/truck. Based on Dar es Salaam's population density, a round-trip distance of less than 1 km was estimated. For modelling simplicity, it was assumed that the participating households were evenly distributed in a square formation, and the truck would drive along the perimeter. Furthermore, it was assumed that households would provide the food waste free of charge, given existing inefficiencies in waste collection systems and the likelihood that households would welcome an opportunity to dispose of waste more effectively, with no additional costs incurred, such as extra storage bins (Mbuligwe & Kassenga, 2004; UN-Habitat, 2021). The technical setup is presented in Figure 55.

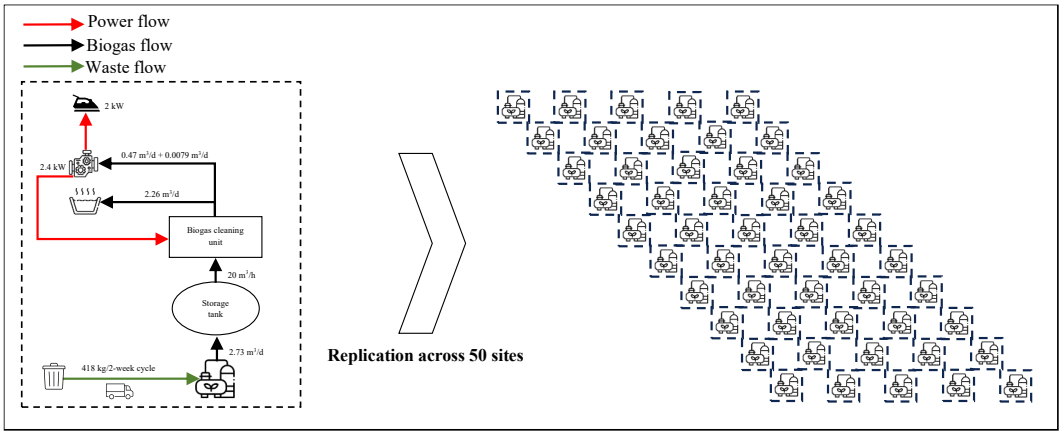

Figure 55. Case study 6: Technical setup of scenario 3

Abbreviations: kg = kilogramme; kW = kilowatt; m^3/day = cubic meter per day; m^3/hour = cubic meter per hour

Financial assumptions were largely consistent with those from scenario 2, incorporating cost considerations for the AD system (CAPEX and OPEX), generator costs (CAPEX and OPEX), biogas stoves, vehicle fuel consumption, fuel prices, and driver salaries. (Allegue & Hinge, 2014; Choudhury et al., 2019). Estimating the cost of biogas cleaning units presents a challenge due to the lack of standardised cost data across different system scales and technologies (Allegue & Hinge, 2014; Choudhury et al., 2019). Available literature provides cost estimates for various systems with differing gas capacities and H_2S removal requirements, making direct comparisons difficult. To maintain a simplified yet reasonable approach, this assessment assumes that the CAPEX of the cleaning unit constitutes 10% of the total AD system CAPEX (Choudhury et al., 2019). Additionally, O&M

costs are derived from average values reported in the literature, rather than being specific to any particular technology. The O&M costs are estimated at 0.028 USD/m^3 of biogas treated (Allegue & Hinge, 2014; Choudhury et al., 2019).

At a 10% discount rate and over 25 years, the project requires an NPC of 339,734 USD, with annual operating costs estimated at 24,927 USD/year. This represents a 29% decrease in NPC and a 53% cost reduction in operating costs compared to the base case. Most of the costs stem almost equally from transportation and logistics (61% of NPC), while generator investment costs account for another 21% of NPC. The CAPEX of the AD and biogas cleaning unit contribute 11% to the NPC. Other minor contributions stem from O&M of the AD system and costs for biogas stoves.

In terms of environmental impact and compared to the base case, total GHG emissions (scope 3 emissions from transportation) were reduced drastically by almost 100%, accounting for only 0.16 $tCO_{2\text{-}eq}$/year.

Scenario analysis summary

This scenario analysis examined different energy access scenarios for 50 women entrepreneurs, evaluating their financial feasibility, operational sustainability, and environmental impact. The results, detailed in Table 33, compare each scenario to the base case. The scenarios were assessed based on initial investment, NPC, annual operating costs, and GHG emissions to provide a comprehensive understanding of their trade-offs.

The base case, requiring no upfront investment, has the highest operating costs and contributes the most GHG emissions due to reliance on conventional fuels. Scenario 1, which transitions entrepreneurs to grid electricity for ironing and LPG for thermal needs, significantly reduces emissions and overall costs compared to the base case, with a relatively low initial investment. However, it remains dependent on fossil-based LPG and grid electricity, which may be subject to price fluctuations and blackouts, respectively. Scenario 2 explores the use of biomethane derived from slaughterhouse wastewater, with three sub-scenarios that differ in cost and emission reduction potential. Economically, costs increase progressively from scenario 2A to 2B to 2C, while GHG emissions decrease accordingly, with the lowest emissions achieved in scenario 2C, followed by 2B and 2A. All sub-scenarios involve relatively high initial investment costs, which become even more substantial with the introduction of a compression unit for storing biomethane in

200-bar pressurised cylinders. These results suggest that biomethane can offer significant environmental benefits, but financial feasibility depends on available investment capital. Scenario 3, which is based on decentralised biogas production from MSW using AD, represents a technically and economically balanced approach. It entails moderate capital investment while achieving a substantial reduction in NPC, outperforming scenario 1. Specifically, it yields a 29% decrease in NPC relative to the base case and simultaneously offers the highest potential for GHG emissions reduction. Although GHG emissions are not eliminated, they remain very minimal. Furthermore, scenario 3 achieves full energy autonomy, making it a viable long-term solution, particularly where minimising grid dependence is advantageous or where improvements in waste management infrastructure are a priority.

Table 33. Case study 6: Comparison of initial investment, NPC, annual operating costs and GHG emissions for the base case and scenarios 1-3

	Initial investment	**NPC**	**Operating costs**	**GHG emissions**
Unit	USD	USD	USD/year	$tCO_{2\text{-}eq}$/year
Base case	0	476,700	52,500	257.69
Scenario 1	3,500	355,900	37,300	75.77
Scenario 2A	628,100	792,800	18,200	18.00
Scenario 2B	840,000	1,008,600	18,600	15.72
Scenario 2C	1,043,300	1,223,200	19,800	12.19
Scenario 3	113,500	339,700	24,900	0.16

Abbreviations: $tCO_{2\text{-}eq}$ = tonne of carbon dioxide equivalent; GHG = greenhouse gas; NPC = net present cost; USD = United States dollar

The choice of the most suitable scenario depends on financial availability, environmental priorities, and the ability to manage the required infrastructure. If minimising investment costs while reducing emissions is a priority, scenario 1

offers an immediate and relatively low-cost improvement. If the focus is on long-term sustainability and significant emission reductions, biomethane-based scenarios provide compelling alternatives, though requiring substantial initial funding. Scenario 3 offers a decentralised, waste-to-energy approach that provides cost-effectiveness and autonomy while having the lowest environmental impact. The decision ultimately hinges on financial resource availability, local infrastructure, and long-term sustainability goals.

7.3.6.3 MTF evaluation

Utilising the World Bank's MTF, this chapter evaluates the three enhancement scenarios of case study 6.

The following assumptions guide the MTF assessment. Regarding capacity, the base case and all enhancement scenarios maintain a tier 5 rating for electrical energy, assuming the use of a 2-kW electric iron consistently across all 50 entrepreneurs. All non-electric energy sources are presumed to fully satisfy demand across scenarios, reflecting the base case situation. Availability and reliability assumptions remain consistent for scenarios 1 and 2, maintaining the same frequency of outages reported by the reference entrepreneur, while non-electric sources are assumed fully available and reliable. Scenario 3 explicitly assumes tier 5 availability and reliability for both electrical and thermal services derived from biogas. Affordability assumptions indicate that electrical costs in scenarios 1 and 2 are equivalent to the grid tariff, maintaining tier 5 performance. LPG costs in scenario 1 slightly exceed the grid tariff, corresponding to a tier 4 affordability rating. Scenarios 2 and 3 assume both electrical and non-electric supplies meet tier 5 affordability requirements, with costs at or below the grid tariff. Legality considerations highlight improvements across all enhancement scenarios, ensuring payments are made exclusively to authorised entities, contrasting the base case where informal procurement of charcoal or firewood occasionally occurs. Convenience significantly improves from the base case, as scenarios 1-3 assume minimal operational impacts on productivity, contrasting the moderate impacts associated with purchasing and operating traditional stoves in the base case. Health evaluations markedly improve from a tier 1 rating in the base case, associated with the indoor use of non-clean fuels, to tier 5 in scenarios 1-3 due to the exclusive use of clean energy sources (BLEENS). Safety also sees substantial improvements, eliminating the risk of accidents related to traditional fuels, which were assumed in the base case.

Figure 56 depicts the progression in energy access tier performance from the base case through scenarios 1-3 for the Tanzanian case study, evaluated using the World Bank's MTF. The assessment highlights a clear incremental improvement, with scenarios 1 and 2 enhancing the overall tier score significantly from tier 1 in the base case to tier 4. Scenario 3 achieves the maximum attainable tier 5, representing the optimal improvement. Notably, non-electric energy performance experiences substantial advancement, moving from a minimum tier 1 in the base case due to traditional biomass use to tier 4 in scenario 1, attributed to LPG implementation, with cost slightly above grid tariffs restricting it from tier 5. In scenarios 2 and 3, the use of biogas successfully achieves a tier 5 rating across all attributes. Across all scenarios, improvements are evident in affordability, legality, convenience, health, and safety attributes, addressing previously negative impacts stemming from traditional biomass use.

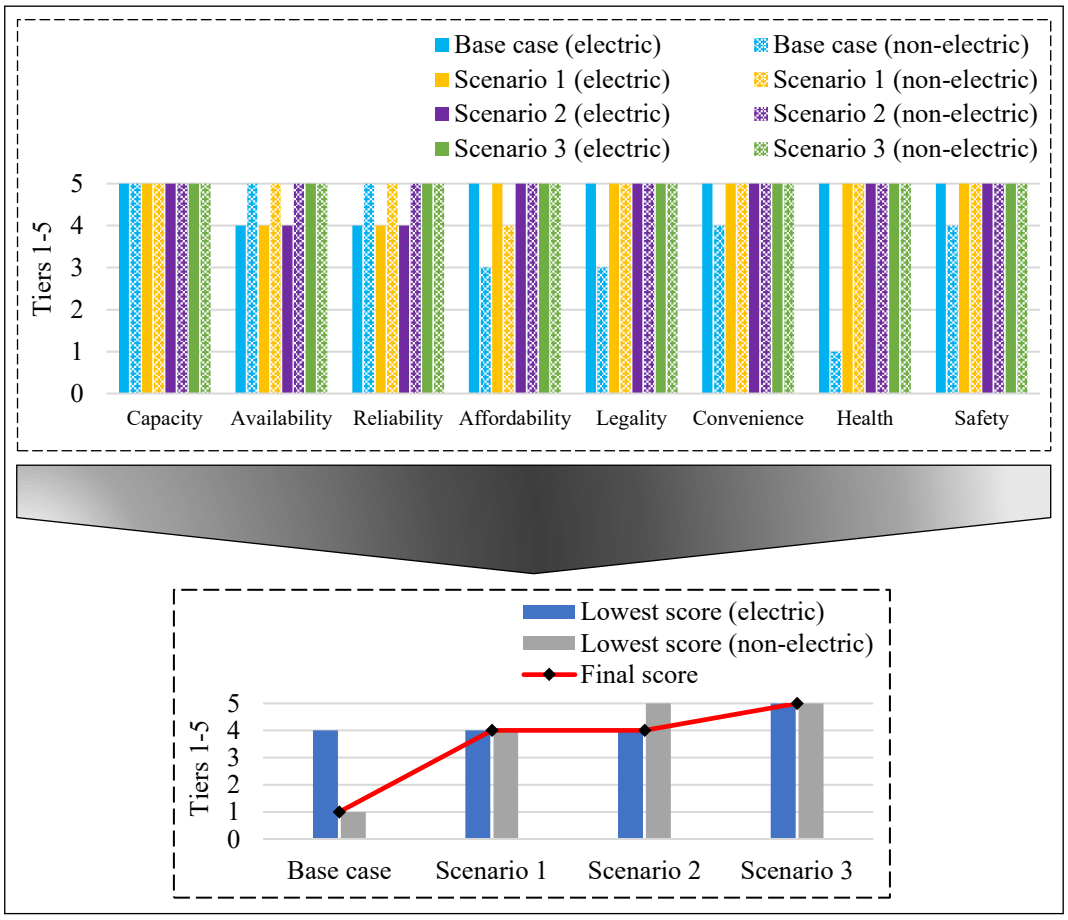

Figure 56. Case study 6: MTF tier performance comparison between base case and scenarios 1-3

These findings indicate substantial advantages gained by transitioning away from traditional biomass fuels toward cleaner, more sustainable energy solutions like LPG and biogas. Scenario 3, in particular, exemplifies how achieving full energy autonomy through renewable energy sources can comprehensively elevate operational sustainability, health, safety, and affordability, assuming energy costs are equal to or lower than existing grid tariffs. Such targeted energy transitions not only significantly enhance productivity and convenience for users but also positively contribute toward broader environmental and socioeconomic objectives.

7.4 Discussion

This chapter set out to address two central research questions: (1) ***how can clean energy technologies be configured to meet the productive energy needs of women-owned enterprises?*** and (2) ***what techno-economic and environmental trade-offs arise when evaluating energy transition scenarios at the enterprise level?*** Drawing on six detailed case studies across Ghana, Tunisia, Kenya, Malawi, Nigeria, and Tanzania, the findings illuminate the multidimensional nature of grid-connected and decentralised clean energy deployment in the productive use sector and the role such interventions can play in improving energy access among women-owned micro- and small-sized enterprises.

The results affirm that grid-connected and decentralised technologies, when selected with care and embedded within context-specific enterprise profiles, can drastically improve energy reliability, displace fossil fuels and traditional biomass, and reduce emissions. At the same time, the analyses reveal important trade-offs related to system complexity, fuel logistics, affordability, and GHG emissions. Collectively, the enhanced scenarios elevated electric and non-electric energy access from baseline tiers 1-3 to tiers 3-5 across all cases, demonstrating significant potential for improved multidimensional access under the World Bank's MTF.

The chapter further highlighted that each case reflects a distinct enterprise profile, energy demand pattern, and geographical setting, offering a granular view of how energy transitions materialise in practice. In Ghana, the shift from traditional fish-smoking kilns to solar PV, LPG, and greenhouse dryers not only improved energy access from tier 1 to tier 4 under the MTF but also reduced reliance on traditional biomass and improved product quality. However, further decarbonisation through coconut husk combustion introduced trade-offs: while locally available and low-cost, biomass combustion reduced the MTF health and

safety scores due to smoke exposure risks, highlighting the tension between circular fuel strategies and clean air standards.

The Tunisian agri-processing enterprise, engaged in olive oil production, achieved full decarbonisation and energy independence under scenario 3 through expanded solar PV, battery storage, and full electrification of olive oil machinery. This configuration not only eliminated diesel dependence but also achieved tier 5 energy access across all attributes.

In Kenya, a jointly owned dairy and cereal processing facility explored four increasingly decarbonised configurations. Scenarios involving full electrification (scenario 3) and biogas integration (scenario 4) achieved tier 5 performance, showcasing the technical feasibility of net-zero operations. In particular, the adoption of circular systems that convert animal waste into energy and fertiliser demonstrates how renewable technologies can support broader enterprise resilience and resource efficiency. However, these systems require coordinated ownership, cooperative governance, and reliable feedstock supply.

In Malawi, scenario 2 achieved complete diesel substitution through solar PV and battery systems in an off-grid maize milling enterprise. This pathway delivered tier 4 energy access, while enabling surplus generation that could potentially be sold to nearby households, offering an example of productive-to-household energy spillovers. Conversely, scenario 3, which involved a syngas-diesel retrofit, offered only partial emissions gains and revealed operational challenges, including complex maintenance, higher capital costs, and uncertain fuel logistics. These findings caution against overly technical or capital-intensive retrofits in low-capacity rural contexts.

Nigeria's leather manufacturing enterprise achieved full electrification using solar PV and electric heating systems, replacing both grid electricity and LPG (scenario 2). This intervention not only reduced emissions and improved energy convenience but also eliminated operational frictions associated with LPG handling. The resulting tier 5 classification on the MTF underscores the ability of electrification, when properly sized, to meet low-to-medium heat demands.

Finally, Tanzania's community-based textile cooperative explored three decarbonisation scenarios. Scenario 3 employed decentralised MSW biogas systems, which achieved the highest emissions savings and tier 5 energy access. Yet this option requires intensive coordination with local governments, ongoing

maintenance support, and cooperative energy governance. Scenarios based on grid electricity and LPG were technically simpler and still delivered significant gains, but offered less emissions mitigation.

Together, these six case studies offer compelling and novel contributions to the discourse on gender, energy access, and productive use transitions in Africa. Most notably, they underscore a critical yet often overlooked reality: energy transitions for micro- and small-scale enterprises must go beyond electrification alone. Addressing thermal energy needs, particularly in sectors such as agri-processing, food production, and textiles, is just as vital. These domains remain underrepresented in energy access models and policy frameworks, yet they are central to women's economic participation across the continent.

Second, the findings challenge the notion of a singular, linear path to decarbonisation. Rather than conforming to idealised models of clean energy transitions, the real-world trajectories observed in these enterprises reveal that hybrid, decentralised, and context-specific solutions often provide greater feasibility, resilience, and uptake potential. Solar PV-diesel hybrids, clean biomass kilns, and modular LPG systems emerge not as second-best compromises but as necessary bridges toward longer-term sustainability.

Third, the research contributes a rare layer of empirical depth. Through appliance-level audits, operational profiling, and scenario-based simulations, it generates one of the most granular datasets available on gendered productive use of energy in Africa. These insights move beyond national averages or sectoral assumptions, anchoring energy modelling in lived enterprise realities. In doing so, the study opens up new possibilities for grounded, demand-driven energy planning that recognises the heterogeneity of women's enterprise pathways.

Yet, these contributions are not without their limits. The technological scope was intentionally bounded to solutions already in use, accessible, or financially viable within the studied contexts. Wind power, micro-hydro, hydrogen, or other emerging technologies, while promising, were excluded due to limited relevance for the enterprises assessed. Moreover, HOMER Pro's modelling architecture, though robust, necessarily simplifies behavioural nuances and temporal fluctuations by relying on average inputs and static assumptions. Likewise, the World Bank's MTF, while a powerful tool for benchmarking energy access, does not capture critical long-term indicators such as system durability and user satisfaction.

To distil these findings visually, Figure 57 summarises the key lessons from the six case studies, highlighting the interplay between technology choice, enterprise realities, and inclusive energy planning.

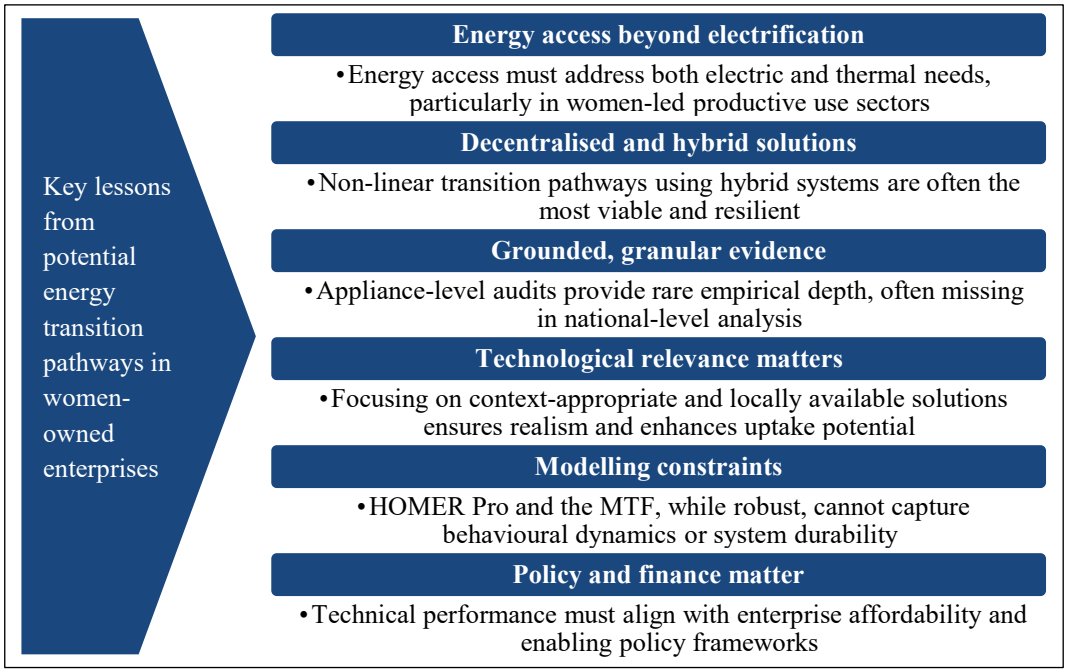

Figure 57. Key lessons from potential energy transition pathways in women-owned enterprises in Africa

Despite the outlined constraints, the results strongly support the view that clean energy technologies, when tailored to enterprise-specific contexts, can significantly enhance productive energy access for women entrepreneurs. These case studies not only reveal persistent gaps and barriers but also demonstrate what becomes possible when energy systems are designed around the lived experiences, constraints, and operational realities of their end users. At the same time, they underscore that technical performance alone is not enough: aligning energy solutions with financial feasibility and supportive policy frameworks is essential.

7.5 Conclusions

This chapter has demonstrated that tailored clean energy interventions can significantly improve energy access for women-owned micro- and small-sized enterprises across multiple African countries, raising performance from MTF tiers 1-3 to tiers 3-5 and delivering measurable gains in reliability, affordability, and

emissions reduction. Drawing on six detailed case studies, the analysis revealed that viable energy transitions emerge not from idealised technologies alone, but from their alignment with real enterprise constraints, ranging from demand profiles and location-specific infrastructure to thermal requirements and fuel availability.

The case studies underscore that context-sensitive configurations, whether involving solar PV, battery storage, LPG, biomass, or biogas, can provide effective and scalable alternatives to conventional fossil-fuel-based systems. However, the simulations also highlight key trade-offs: cleaner technologies may reduce emissions while increasing capital costs, or improve energy reliability while introducing operational complexity. These tensions reinforce that technological viability is only one part of the equation.

Ultimately, the feasibility of low-carbon transitions depends on the surrounding institutional and financial architecture. Even the most promising technical solutions risk stalling without suitable business models, accessible financing, after-sales service ecosystems, and gender-responsive support structures. Addressing these systemic conditions is the focus of the next chapter.

Chapter 8 shifts from scenario analysis to implementation strategy. It interrogates how the interventions explored here can be enabled, financed, and scaled within existing regulatory, policy, and financial frameworks. In doing so, it completes the research arc from diagnosis and design to delivery, embedding sustainable energy transitions within local contexts.

Chapter 8

8. Enabling clean energy transitions – Which business models and financing mechanisms support enhanced energy access for women entrepreneurs?

8.1 Introduction

Delivering reliable and affordable energy for productive use is increasingly recognised as a foundation of inclusive and sustainable economic development across Africa (Fajardo et al., 2025; Falchetta et al., 2022). Yet financing such systems, especially for women-owned micro- and small-sized enterprises, remains structurally complex. The challenges extend beyond capital scarcity to include fragmented financial ecosystems, limited risk-sharing mechanisms, and gender-based constraints in access to credit and asset ownership (Ingole, 2024; Pueyo, Carreras, et al., 2020). As suggested in the previous chapter, even the most promising technical configurations for enhanced energy systems are unlikely to succeed unless they are embedded within appropriate delivery and financing models that reflect the realities of their users and contexts.

This chapter addresses that critical gap by exploring how clean energy transitions can be delivered, financed, and sustained in practice. It is guided by a central research question: ***what kinds of business models and financing schemes are most appropriate to support women-owned enterprises under enhanced energy access scenarios in diverse African contexts?***

The chapter begins by examining how the literature conceptualises business models, access to finance, and risk mitigation in the context of clean energy for

productive use. Drawing on a quasi-systematic review of nearly 100 scholarly sources, of which around 30 focus explicitly on productive use, the review highlights how these elements are interdependent and embedded within broader institutional and market ecosystems. Rather than viewing business models and financing instruments in isolation, the review situates them within dynamic policy landscapes and evolving donor priorities.

Building on this foundation, this chapter turns to a comparative synthesis of the six country case studies from Chapter 7 (i.e., Ghana, Kenya, Malawi, Nigeria, Tanzania, and Tunisia). It assesses which business models and financing mechanisms are best suited for supporting the suggested energy transitions, taking into account regulatory frameworks, access-to-finance barriers, and gender-responsive policy instruments. In doing so, it moves from theoretical and review-based insights to practical, empirically grounded configurations for implementation. In other words, the case studies illustrate how financing and delivery models can be shaped by enterprise-level realities across different national contexts.

8.2 Materials and methods

The central premise of this chapter, that viable business models and financing schemes are essential to realising clean energy transitions for women-owned enterprises, requires a methodological approach that is both conceptually grounded and empirically adaptable.

A two-pronged research approach was adopted here. First, a quasi-systematic literature review was conducted to map current academic and policy thinking on financing and business models for renewable energy, with a specific emphasis on productive use. This review provided the conceptual scaffolding to understand the state of knowledge, identify recurring analytical themes, and extract operational models with potential transferability. Second, a comparative case analysis was applied, structured around a hybrid thematic framework. This approach integrated quantitative indicators and qualitative assessments to evaluate the fit between energy performance outcomes, regulatory environments, and gender-responsive delivery options for each country case.

To visualise this mixed-methods approach, Figure 58 provides a schematic overview of the dual-method research design used to identify viable business

models and financing schemes for clean energy transitions in women-owned enterprises.

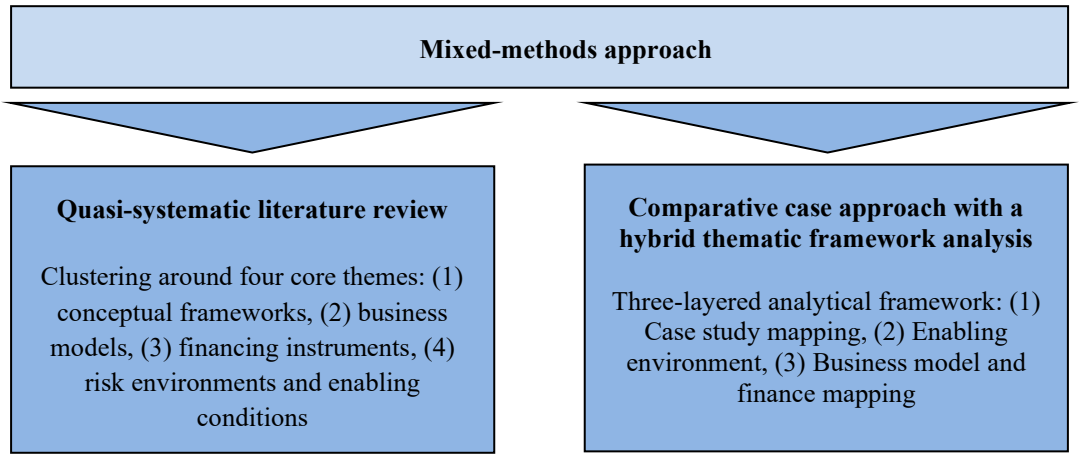

Figure 58. Schematic overview of the mixed-methods approach to identify viable business models and financing schemes for country case studies

The following sub-sections detail the two components of this methodology. Section 8.2.1 outlines the literature review strategy, including search logic, thematic filters, and selection criteria. Section 8.2.2 describes the comparative case approach, including case study mapping, enabling environment diagnostics, and the strategy adopted to map potential business models and finance mechanisms.

8.2.1 Quasi-systematic literature review

To establish a conceptual basis for evaluating business models and financing schemes, the analysis begins with a review of the academic literature. The methodological approach is grounded in a structured, replicable search process using the Scopus database, targeting peer-reviewed articles, review papers, conference proceedings, and books. The search was conducted by querying terms related to “financing models/schemes” and “business models/cases”, filtered through article titles, abstracts, and keywords. Two primary thematic anchors guided the search logic: productive use and, more broadly, energy and electricity access. To ensure comprehensive coverage, Boolean operators and wildcards were applied to enable flexible identification of variant terminologies while minimising irrelevant results. The review did not restrict the geographic scope during the search phase, acknowledging that valuable insights, particularly on business and financing

models, can transcend regional contexts. Nevertheless, Africa remained the analytical focus of the final review.

The initial search yielded 272 papers, of which 58 explicitly addressed productive use. After applying filters for language (English only) and ensuring relevance to the disciplinary scope of the study (e.g., energy studies, development, economics, and environmental sciences), a refined corpus of 265 papers was identified, with 55 addressing productive use directly. Subsequent abstract screening assessed relevance based on criteria such as thematic alignment and practical insights into financing or business models. This process led to a selection of 97 papers, with 30 focused on productive use, forming the evidentiary base for this review.

The temporal distribution of the final set spans from 2008 to 2025, capturing the evolving discourse over nearly two decades. While some of the earliest scientific literature on mini-grids in Africa emerged around 2005 (Fajardo et al., 2025), more focused academic attention on financing mechanisms and business models for productive use gained momentum only a few years later. This study, therefore, builds upon and contributes to this relatively recent but increasingly critical strand of research. Notably, 32% of the selected papers were published in 2024 or 2025. An additional 40% were published between 2020 and 2023, while 16% fell between 2015 and 2019, and the remaining 12% were published before 2015. This distribution highlights both historical continuity and a significant recent surge in attention toward financing and business models for energy access and productive use.

Geographically, the studies were classified by the regions covered in their research, not by author affiliation or publication outlet. Over half (54%) focused on Africa, either through continent-wide analyses, sub-Saharan regional scopes, or specific African countries. Developing countries in general accounted for 18%, and global comparative studies for 9%. The remainder were studies centred in Asia (15%) and a small proportion (3%) from Latin America and Eastern Europe.

These findings align with a recent bibliometric study by Odoi-Yorke et al. (2024) that examined 267 publications on mini-grid research for rural electrification between 2003 and 2023, also using Scopus. That study revealed a marked increase in publications over the last decade. It identified hybrid systems, business models, and policy frameworks as core themes, with Africa and South Asia as prominent deployment contexts. Importantly, it underscored growing attention to

socioeconomic dimensions and the need for context-sensitive, interdisciplinary approaches, mirroring the insights emerging from the present review.

To facilitate analytical coherence and comparability, the reviewed literature was thematically clustered into four core categories, each reflecting a critical dimension of renewable energy deployment for productive use: (1) analytical perspectives and conceptual frameworks; (2) business model configurations; (3) financing instruments and capital flow mechanisms; and (4) risk environments and enabling conditions. This clustering enabled the identification of recurring patterns, gaps, and emerging innovations within and across thematic domains.

While the literature review provided important conceptual orientation and identified typologies of business and financing models, it remained abstracted from the lived realities and institutional conditions that shape energy access on the ground. To bridge this gap, the next sub-section presents a comparative case methodology, grounded in empirical data from six country case studies. This hybrid approach combined scenario-level performance metrics with a structured diagnostic of national enabling environments to evaluate the contextual feasibility of selected business model configurations.

8.2.2 Comparative case approach with a hybrid thematic framework analysis

Building on the insights derived from the literature review, this section outlines the analytical approach used to evaluate viable business models and financing mechanisms across the six empirical case studies. Recognising the layered complexity of productive use energy transitions, the method applied reflects a mixed-methods research design, encompassing both quantitative and qualitative strands within a hybrid thematic framework analysis. It employs comparative case logic and draws on institutional toolkits and development finance methodologies to enhance analytical coherence and gender responsiveness. This approach is warranted given the complex, multi-scalar nature of the research problem, which spans technical, institutional, and socio-gendered dimensions (Feredey & Muir-Cochrane, 2006; Peterson Combs & Onwuegbuzie, 2010; Schoonenboom & Johnson, 2017; Srivastava & Thomson, 2008). While traditionally defined as mixed methods, the approach further integrates hybrid reasoning, more specifically, deductive, where known models and frameworks inform the initial categorisation, and inductive, where case-specific evidence guides refinements (Feredey & Muir-Cochrane, 2006; Srivastava & Thomson, 2008). This anchors the analysis in both

established theory and grounded insights. Three core components structure the investigation: scenario-level energy and environmental performance, country-level enabling environment diagnostics, and literature- and framework-informed mapping of contextually viable business and financing models.

As a starting point, each scenario of the respective country case was characterised using empirical performance indicators developed in the earlier quantitative assessment. These include the increase in energy access tier (based on the World Bank's MTF), CAPEX and annual operating costs (USD), independence from fossil fuels and/or the electric grid, reliability issues (yes/no), and the expected GHG emissions avoided ($tCO_{2\text{-}eq}$/year). Where scenarios included multiple sub-options, CAPEX values are presented as a rounded range from the lowest to the highest configuration, while for GHG emissions, a conservative approach is used by reporting the lowest avoided emissions value. This ensures the analysis reflects minimum assured performance across cost and environmental dimensions. The scenario-level data serve as a base upon which institutional conditions and business models must be mapped.

Second, the enabling environment was evaluated in each country using internationally recognised indicators that serve as proxies for regulatory stability, market readiness, and gender inclusion. These include: the World Bank's Ease of Doing Business Index, the Business Ready report, the African Development Bank's Electricity Regulatory Index (AfDB's ERI), and the World Economic Forum's Global Gender Gap Index. The Ease of Doing Business Index was used to ensure comparability across all countries in the study sample, recognising that it was the most widely cited business climate metric prior to being discontinued (The World Bank Group, 2020). For Ghana and Tanzania, the more recent Business Ready report was additionally consulted to reflect updated reform benchmarks (The World Bank Group, 2024a). The ERI provides a composite view of the quality of electricity sector regulation, assessed through three sub-pillars: Regulatory Governance Index (RGI), which evaluates the legal and institutional mandate of the regulator; Regulatory Substance Index (RSI), which captures implementation quality; and Regulatory Outcome Index (ROI), which reflects perceived performance outcomes by utilities and consumers (African Development Bank (AfDB) Group, 2022). Countries are scored from 0 to 1, and categorised as low (0.000-0.499), medium (0.500-0.599), substantial (0.600-0.799), or high (0.800-1.000) regulatory performance, enabling a nuanced comparison of enabling conditions for investment. The Global Gender Gap Index offers an annual, cross-national measure of gender equality in four domains: economic participation,

education, health, and political representation (World Economic Forum (WEF), 2024). Introduced in 2006, it is the longest-standing index tracking progress in narrowing gender disparities and was used to assess both structural constraints and opportunities for women in productive use value chains. These indicators were selected not only for their methodological rigour and global comparability but also because they impact enterprise formation, electricity service provision, and women's capacity to access and benefit from enhanced energy services. Their combined interpretation thus forms a diagnostic lens through which the feasibility, inclusiveness, and contextual viability of specific business and financing models were assessed.

To enrich and contextualise these quantitative indicators, an in-depth review of each country's energy policy ecosystem and gender support architecture was conducted. This drew on scientific and grey literature, including national electrification plans, clean energy subsidies, donor programmes, and policy reports. Rather than treating these areas in isolation, the analysis integrated multiple themes related to energy access and gender inclusion, ranging from grid and off-grid programmes, tariff and subsidy mechanisms, institutional and financial structures, to gender mainstreaming in national strategies, as well as potential enterprise support and financial inclusion for women entrepreneurs. This thematic synthesis allowed for a systems-level understanding of how intersecting policy, institutional, and socio-economic factors shape the feasibility and inclusiveness of productive use interventions.

Third, to link these insights with actionable business models and financing schemes, a structured analytical framework was developed, aligning with scientific practice in framework analysis and hybrid model-building approaches (Feredey & Muir-Cochrane, 2006; Srivastava & Thomson, 2008). Drawing from the literature review, a set of business model configurations (e.g. anchor-client logic, A-B-C model, PAYGo, lease-to-own, cooperatives, PPPs) and financing mechanisms was identified (e.g. concessional loans, grants, blended finance, microfinance, credit guarantees). Each case was then assessed against this matrix to determine the most suitable configurations in light of its performance outcomes and enabling environment. The analysis used a hybrid deductive-inductive logic: deductively applying known models and finance structures, and inductively refining or adapting them based on contextual fit.

Table 34 presents the analytical matrix used for this assessment. It should be noted that this study did not apply the Business Model Canvas or similar structured

modelling tools to prescribe fully defined business models or financing architectures for each case (Dibaba et al., 2023). Instead, a context-sensitive, framework-based approach was adopted that synthesises the enabling environment, drawing on both quantitative performance indicators and qualitative policy, institutional, and financial landscape assessments to sketch contextually grounded and potentially viable business and financing pathways. This exploratory design allows for alignment with the socio-economic and regulatory realities specific to women-owned productive use enterprises, while acknowledging that the feasibility of implementation depends on numerous unobserved local factors. This analysis is deliberately illustrative rather than definitive, offering indicative configurations that may be adapted or elaborated upon through future applied research or field-level feasibility assessments. In particular, more granular diagnostics of enterprise-level constraints, user affordability thresholds, and ecosystem readiness would be potentially necessary to validate and operationalise the proposed models. These refinements, ideally co-developed with local stakeholders and financiers, represent a critical frontier for future inquiry.

Table 34. Comparative analytical matrix of the applied hybrid thematic framework analysis

(1) Case study mapping: Scenario context and energy access performance

Quantitative						
Tier increase from the base case	Scenario MTF performance	Independence from the electric grid and/or a fossil fuel generator	Energy availability or reliability is an issue	CAPEX	Annual operating costs	GHG emissions avoided
Number of tiers	*Final tier*	*Yes/no*	*Yes/no*	*USD*	*USD/year*	*$tCO_{2\text{-}eq}$ avoided/year*

(2) Enabling environment: Policy, institutional and financial dimensions

Quantitative				Qualitative	
World Bank's Ease of Doing Business report	World Bank's Business Ready report	ERI	Global Gender Gap Index	Energy access programme or scheme	Gender-focused support scheme
Score and rank	*Score and rank*	*Low/medium/substantial/high level*	*Score and rank*	*Grid and off-grid programmes, tariff and subsidy mechanisms, institutional and financial structures*	*Gender mainstreaming in national strategies, Enterprise support for women entrepreneurs, Financial inclusion for women entrepreneur*

(3) Business model and finance mapping: Delivery logic and capital mechanisms

			Qualitative			
Anchor model	Ownership delivery model	Revenue stream	Public finance	Private finance	Subsidy	Risk-sharing instrument
Anchor logic, A-B-C model, or bundling	*Entrepreneur-led, cooperative, PPP, lease-to-own, PAYGo*	*Single or multiple*	*DFI, government, donor*	*Commercial bank, equity fund, venture capital, and/or impact investor*	*Yes/no, type*	*Grant, concessional loan, equity, blended finance, lease, microfinance, or cooperative pool*

Notes: It is acknowledged that the selected resources and databases used within the second methods strand span different publication years, ranging from 2020 to 2024. Despite temporal variation, all metrics were chosen for their methodological robustness, data availability across the case countries, and relevance to assessing the regulatory, institutional, and gendered dimensions of productive use.

The framework design itself was shaped by existing toolkits from AfDB, ADB, UNDP, and ENERGIA. The ten-component Integrated Framework for Women's Enterprise Development by the AfDB and ILO (Stevenson et al., 2007) guided this study on how to incorporate institutional enablers such as capacity building, business development services, legal frameworks, or access to financial resources. This was particularly influential in structuring the gender-related themes, which focused on gender in national energy policy and strategy, enterprise support and productive use programmes, and finance and inclusion gaps. These categories were used consistently across countries. The ADB's gender toolkit (ADB, 2012) and UNDP's gender-responsive energy design frameworks (UNDP, 2004, 2022) provided principles for assessing affordability, capacity, and ownership pathways for women entrepreneurs. These sources predominantly advocate for rental models, microfinance access, and PPPs that explicitly include women as franchisees, service providers or productive users, features that informed the evaluation of model suitability. ENERGIA's multi-level framework on women's energy entrepreneurship added an ecological logic to this method: evaluating each scenario at the individual (skills, agency), community (norms, networks), and institutional (regulations, finance) level (Shankar et al., 2019). This reinforced the multi-scalar approach, ensuring business models were not evaluated purely from an enterprise or project lens, but also considered social and structural barriers to women's inclusion.

By critically engaging these external frameworks and toolkits, the methodology is not reinventing the wheel but rather standing on the shoulders of existing knowledge. However, the framework remains cautious to adapt rather than adopt wholesale. For example, AfDB's ten-component framework (Stevenson et al., 2007) is broad and may not fully capture energy-specific nuances, so it is adapted to focus on the components most pertinent to enterprises (access to finance, business development services, networks, policies). The ADB and UNDP toolkits (ADB, 2012; UNDP, 2004) provide a variety of gender inclusion measures for the energy sector in general, and again, those relevant to productive use were considered. In essence, the methodology is informed by these frameworks but tailored to the specific research question on productive use business models.

The rationale for this hybrid methodology rests on four pillars. First, it allows system-level integration of technical, institutional, financial, and gendered dimensions of energy access, as advocated in integrative frameworks for sustainable energy transitions (Ockwell & Byrne, 2016; UNDP, 2022). Second, it

offers transparency and replicability through a clear audit trail from data to recommendation, in line with the principles of thematic framework analysis (Feredey & Muir-Cochrane, 2006; Srivastava & Thomson, 2008). Third, it operationalises gender mainstreaming not as an outcome variable but as a methodological principle, following guidance from ENERGIA (Ruggles et al., 2019), UNDP (UNDP, 2004), and the ADB (ADB, 2012). Fourth, it supports a model-building logic appropriate for emerging, context-sensitive fields like productive use in women-owned enterprises, drawing on both deductive typologies and inductive insight generation (Feredey & Muir-Cochrane, 2006).

8.3 Results

Building on the methodological foundations, this section presents the empirical core of the chapter, where conceptual insights, literature synthesis, and case-level diagnostics converge to investigate how energy systems can be most effectively delivered and financed to support productive uses in women-owned enterprises. The results unfold in three interlinked stages, each corresponding to a building block of the analytical architecture developed in the preceding sections.

The first part (8.3.1) introduces the conceptual framework, which anchors the analysis in a structured understanding of business models, financing instruments, and risk environments relevant to decentralised and grid-connected energy transitions.

The second part (8.3.2) presents insights from the quasi-systematic literature review. This synthesis distils trends and gaps in how business models and financing mechanisms are conceptualised and deployed in practice, particularly for productive use interventions in low-income or underserved contexts. It also draws attention to underexplored risks and structural enablers that condition the feasibility of inclusive energy solutions.

The final part (8.3.3) turns to the empirical case study assessment. Here, the conceptual and literature-derived frameworks are operationalised to assess which business and financing configurations align most closely with the technological realities, institutional conditions, and gender dynamics observed across the six African case contexts. The analysis matches scenario-based energy interventions to delivery and financial models, offering context-sensitive strategies for implementation.

Together, these results move the analysis from theory to application, from the abstract design of energy systems to the grounded realities of enterprise adaptation and viability.

8.3.1 Conceptual framework

In this study, energy access is primarily conceptualised through the lens of decentralised energy systems, with particular emphasis on micro- and mini-grids (Dibaba et al., 2023; Fajardo et al., 2025; Falchetta et al., 2022). While grid extension continues to play a role in electrification, especially in urban and peri-urban centres, it remains largely peripheral in current debates around business models and financing strategies for productive use in rural and underserved settings. In line with this trend, the scenario analysis discussed in Chapter 7 engaged with grid-connected options only where net metering was technically and economically feasible. The overarching analytical focus, however, remained on decentralised, autonomous configurations. These systems are more attuned to the infrastructural realities and dispersed settlement patterns common in many African contexts and are increasingly recognised as the backbone of inclusive energy transitions. Among these, micro- and mini-grids stand out for their scalability, modular design, and ability to deliver reliable power for income-generating activities (Dibaba et al., 2023; Falchetta et al., 2022).

Understanding how such systems are financed, delivered, and sustained goes beyond the cataloguing of technical solutions or policy instruments. It requires a structured conceptual framework capable of identifying commonalities, contextual constraints, and innovation levers across diverse implementation settings. In doing so, the framework builds on prior conceptual work that classifies business models, financing mechanisms, and risk environments in the off-grid energy sector (Dibaba et al., 2023; Fajardo et al., 2025; Falchetta et al., 2022), but has been adapted to reflect this study's specific focus on women-owned enterprises and productive uses of energy across African contexts.

8.3.1.1 Business models

At the heart of delivering sustainable energy services lies the question of how value is generated, delivered, and captured, an inquiry encapsulated in the concept of the business model (Dibaba et al., 2023). The notion dates back to early economic thinking in the mid-20th century, gaining academic and commercial prominence in the 1990s with the rise of digital and e-commerce platforms. In the energy access

space, a business model provides the structural blueprint through which an energy service provider organises its operations, monetises its services, and distributes risk and returns among stakeholders.

The provision of energy services in the context of decentralised renewable energy has evolved through a variety of business model configurations, reflecting the diversity of institutional, technical, and socio-economic environments across regions (Dibaba et al., 2023; Fajardo et al., 2025). One critical axis of classification focuses on ownership and operational responsibility (Fajardo et al., 2025). At one end of the spectrum lie publicly operated utility models, where energy systems are developed and managed by government entities. These arrangements benefit from state backing but often face operational inefficiencies, particularly in rural or peri-urban contexts. On the other end are privately owned models, wherein commercial actors design, finance, and operate energy infrastructure. These tend to be more agile and performance-driven but can struggle to align with equity and affordability goals. Between these poles are hybrid ownership arrangements, which combine public oversight with private-sector dynamism. These include public-private partnerships (PPPs), renewable energy service companies, concession-based delivery, and power purchase agreements (PPAs). Such structures attempt to leverage public capital or regulatory support while drawing on private sector expertise and financing. Community-owned models also constitute an important category, particularly where localised governance structures are strong. In such cases, energy systems are financed and operated by local cooperatives or village associations, often with external technical assistance.

Another dimension of business model differentiation concerns the targeted user base (Fajardo et al., 2025). Some models are designed with a focus on households and micro-enterprises, aiming to provide low-tier energy services suitable for lighting, phone charging, and basic appliances. Others adopt what is known as the anchor-business-consumer (A-B-C) approach, in which large, energy-intensive users, such as telecom towers, agri-processors, or commercial enterprises, serve as stable off-takers whose demand helps to underwrite the costs of supplying smaller residential users (Dibaba et al., 2023; Fajardo et al., 2025; Falchetta et al., 2022). This strategy improves financial viability by anchoring revenue streams to reliable consumers.

Closely tied to ownership and consumer strategies are the mechanisms through which costs are recovered (Fajardo et al., 2025). For-profit models aim to achieve full cost recovery through tariffs, often complemented by appliance sales or value-

added services. However, this is not always feasible in low-income or sparsely populated areas. As a result, partially subsidised approaches are widely used, combining user payments with external grants or concessional finance. Fully subsidised models, while uncommon in commercial practice, may be implemented in humanitarian or government-led electrification efforts, particularly where the goal is universal access rather than financial sustainability.

Finally, bundling strategies have gained prominence as a means of enhancing model resilience and customer value (Fajardo et al., 2025). Operational bundling refers to the integration of multiple services, such as energy, water, and digital connectivity, under a single delivery platform. Portfolio diversification involves the development of varied project types, geographies, or customer segments to spread risk and increase investor appeal. Financial bundling, meanwhile, encompasses strategies such as pooling projects to access larger tranches of capital or blending concessional and commercial finance to improve the investment profile of electrification ventures.

8.3.1.2 Access to finance

The question of how these business models are funded is central to their feasibility and scale. Financing can be distinguished by its source and its form, which shapes the risk-return profile and implications for project design (Fajardo et al., 2025). Financing sources can be broadly divided into public and private channels. Public sources include development finance institutions (DFIs), multilateral and bilateral donors, and government-backed climate investment mechanisms. These entities often provide concessional capital or guarantees to de-risk private investments, particularly in underserved regions. Private sector financing is diverse and includes commercial banks, private equity funds, venture capital firms, and impact investors. Each type of investor brings different expectations regarding return profiles, risk tolerance, and time horizons. Commercial banks typically require strong collateral and predictable revenue streams, which can be difficult to ensure in rural energy markets. Impact investors, on the other hand, may accept lower returns in exchange for measurable social and environmental outcomes. Venture capital is more likely to support early-stage innovation but demands high growth potential.

Beyond the source, the type of finance is also a critical variable (Fajardo et al., 2025). Debt finance is the most common form of capital but is also the most challenging to secure for smaller developers. Commercial loans, often provided by

local banks, tend to carry high interest rates and short repayment periods. Their provision is further constrained by a general lack of familiarity with decentralised energy technologies, which increases the perceived risk. Concessional loans, usually issued by DFIs or national energy agencies, offer more favourable terms but are often difficult to access due to complex due diligence requirements and high transaction costs. These barriers disproportionately affect small and community-based developers who lack the balance sheets, collateral, or formal status needed to qualify. Equity investment is primarily sourced from impact funds, developers themselves, or corporate sponsors. However, equity inflows are limited by uncertainty about business models, as well as investor unfamiliarity with mini-grid markets. Most equity investors prefer established firms with demonstrable performance records and operating assets. Project finance, where debt and equity are raised for a specific infrastructure project based on future cash flows, remains rare and is usually restricted to large-scale developers. Corporate finance, based on the company's overall assets and reputation, is slightly more accessible but still constrained. Subsidies, another type of finance, remain essential to energy access scale-up. CAPEX subsidies reduce upfront investment burdens, while demand-side subsidies address affordability gaps among consumers. Despite their importance, subsidies are frequently entangled in bureaucratic processes, are limited in scope, and are subject to competition and donor conditions that can restrict implementation flexibility. Results-based financing (RBF) on the other hand offers an alternative approach by providing financial support after measurable outcomes are delivered, such as the number of new household or business connections.

8.3.1.3 Key risks

Renewable energy projects in Africa, including those targeting productive use, face a multi-dimensional risk environment (Dibaba et al., 2023; Fajardo et al., 2025; Falchetta et al., 2022). These risks can be categorised broadly as external and internal (Fajardo et al., 2025). External risks pertain to the broader institutional and market ecosystem. Regulatory uncertainty, whether in licensing procedures, tariff approval, or grid extension policy, can deter investment and hinder planning. Limited market access, particularly in remote areas, affects both the demand base and supply chain logistics. Macroeconomic instability, currency fluctuations, and political unrest further compound risk profiles, especially for foreign investors. Internal challenges relate to factors within the control of developers and operators, albeit often influenced by the external environment. Chief among these is customer creditworthiness and payment reliability. In regions with high poverty rates or irregular incomes, ensuring timely payments can be extremely difficult, leading to

cash flow problems and increased default risk. Governance issues within energy enterprises, ranging from weak managerial capacity to misaligned incentives, can erode operational performance. Human resource limitations, including the scarcity of trained technicians and managerial staff, also hinder scalability. Finally, community engagement remains a perennial challenge, as insufficient consultation or poorly managed expectations can result in low uptake or active resistance, especially in contexts where energy services intersect with broader livelihood dynamics.

Together, these conceptual dimensions offer a structured lens for interpreting the empirical evidence assessed in this review. With this conceptual foundation in place, the chapter now turns to the results obtained from the quasi-systematic literature review on business models and financing mechanisms for decentralised energy systems. The following section maps prevailing analytical perspectives, implementation models, financing channels, and enabling conditions that have shaped the discourse on productive use electrification over the past two decades.

8.3.2 Insights from the literature: Business models, finance, and risks in productive use energy systems

Building on the conceptual distinctions introduced in the previous section, this section presents the results of the quasi-systematic literature review, offering an empirically grounded synthesis of current debates and applied models relating to the financing and delivery of renewable energy systems for productive use in Africa. Rather than providing a fragmented overview of isolated findings, the review is organised into four interrelated analytical clusters, reflecting the core pillars identified in the conceptual framework: analytical perspectives, business models, financing instruments, and the broader risk and enabling environment.

The first cluster distils key theoretical contributions and comparative assessments that frame the role of business models and finance in energy access, with particular emphasis on productive use as a viability driver for decentralised systems. This includes insights into demand aggregation, cross-subsidisation, and the often-overlooked integration of environmental performance indicators. The second cluster explores the diversity of business model configurations emerging across the continent, ranging from anchor-client structures to PAYGo and community-led models, while investigating how ownership forms, revenue logic, and service bundling shape sustainability outcomes. The third cluster shifts focus to financing, unpacking capital flow patterns, the relative roles of concessional and

commercial instruments, and innovations such as RBF, blended structures, and microfinance models. Finally, the fourth cluster synthesises the risk architecture within which these systems operate, mapping both internal and external risks, from regulatory volatility and fuel logistics to user payment reliability and technical servicing capacity.

8.3.2.1 Analytical perspectives

The literature on renewable energy systems for energy access in Africa, particularly for productive use, is marked by a shift from technology deployment toward systemic, institutional, and financial thinking. No longer viewed as merely a development co-benefit, productive use is increasingly framed as a structural necessity for the economic viability of decentralised energy systems (Dagnachew et al., 2023; Mukoro et al., 2022). The analytical perspectives reviewed in this section reflect this evolution, offering a rich set of frameworks and cross-cutting insights that inform how energy access is conceptualised, evaluated, and financed.

Foundational contributions emphasise the need for dynamic and integrative frameworks to evaluate business models beyond technical delivery. One such approach (Dibaba et al., 2023) introduces a structured framework for continuous assessment of mini-grid performance, incorporating financial, operational, and stakeholder dimensions. As mini-grids grow more complex, with multiple actors involved in value creation, the paper stresses that business models must evolve in real-time, accounting for shifting customer bases, investment cycles, and community expectations. Similarly, Boche et al. (2022) argue that financial viability depends on the co-alignment of social, informational, and institutional subsystems. By treating mini-grids as embedded infrastructures rather than standalone assets, this work underscores the importance of system-wide diagnostics in shaping long-term outcomes.

Moving from evaluation frameworks to design typologies, several studies highlight the critical role that demand stimulation, particularly through productive use, plays in business model sustainability. Papers by Erdiwansyah et al. (2023) and Mukoro et al. (2022) demonstrate that mini-grids, unlike solar home systems, depend on increased and consistent electricity consumption to ensure cost recovery. In both analyses, productive use is not merely a secondary benefit but a core component of financial logic. However, prevailing models frequently fail to integrate mechanisms such as appliance financing, access to working capital, or local business support, which are necessary to enable meaningful uptake of

productive electricity use. Importantly, both studies also highlight a significant blind spot in the literature: the near-absence of environmental sustainability metrics in business model assessments. While energy access initiatives often position themselves within a broader sustainability agenda, few include environmental indicators in the evaluation of their business strategies. Erdiwansyah et al. (2023) call explicitly for future research to incorporate environmental performance as a core component of energy access assessments, arguing that policies without such metrics risk being incomplete or counterproductive. This omission is echoed in Mukoro et al. (2022), which stresses the importance of a "triple bottom line" approach, one that balances social, economic, and ecological outcomes.

A more granular analysis of mini-grid business models in sub-Saharan Africa is offered by Fajardo et al. (2025), which focuses on hybrid configurations like anchor-business-consumer (A-B-C) models and project bundling. While these approaches offer theoretical gains in stability and scale, the study finds that demand volatility, consumer affordability constraints, and limited access to concessional capital reduce their replicability in rural settings. It emphasises that financing strategies must be highly adaptive, with layered capital structures and risk mitigation tailored to context, especially where productive use is central to the value proposition. It is in this context that productive use-specific analyses add critical insight. Aarakit et al. (2024), through a systematic review of 54 studies, show that electricity access alone is rarely sufficient for productive transformation. Uptake of productive use depends on access to credit, financing for appliances, and business development services, all of which remain underdeveloped in most rural energy programmes. Crucially, the study finds that traditional microfinance instruments are poorly suited to the working capital needs of small enterprises, whose investment horizons and risk profiles differ markedly from household consumers. Complementing this, Dagnachew et al. (2023) model the effects of integrating productive use into energy planning scenarios. Their study demonstrates that accounting for productive use can increase projected household demand by up to 50%, changing both the scale and composition of viable electrification pathways. However, this heightened demand also requires greater upfront investment, underscoring the importance of hybrid financing models that blend public support with private capital. The paper cautions that if productive use is not explicitly planned for, from both a technical and financial standpoint, rural electrification risks falling into a subsistence model, unable to deliver economic transformation. These productive use-centred insights are echoed and expanded in broader macro-financial critiques. Bhattacharyya (2013) finds that the current architecture of energy finance is fundamentally inadequate for achieving universal access.

Investment flows are both insufficient and misaligned, favouring household-level access over enterprise-focused delivery. Similarly, Zerriffi (2011) stresses the importance of bridging supply- and demand-side financing instruments to move beyond traditional aid-driven approaches and instead focus on innovative financial mechanisms that support both energy producers and consumers.

Together, these analytical contributions signal a departure from electrification as a linear process of connection and toward a model of energy access that is systemic, dynamic, and grounded in productive potential. Productive use emerges not as a secondary benefit but as a strategic necessity, one that redefines how business models are structured, how capital is mobilised, and how impact is measured. The challenge ahead lies not only in deploying infrastructure but in aligning financial tools, institutional frameworks, and end-user energy services to support a development pathway where energy carriers are a catalyst, not a ceiling.

8.3.2.2 Business models

Business models play a pivotal role in shaping the financial viability and delivery of renewable energy for productive use, particularly in rural and underserved areas of Sub-Saharan Africa and beyond. As this literature shows, innovation is not limited to technology or financing instruments but extends to the very architecture of how energy services are structured, delivered, and embedded within broader economic systems. The review reveals a wide array of model structures, ranging from utility-led and entrepreneurial service models to hybrid ownership and community-based arrangements (Cabraal, 2012; Katre et al., 2019; Ogeya et al., 2025), as well as dynamic shifts in value propositions that combine electricity with other services or sectoral integrations (Garcia et al., 2024; P. Trotter, 2019; Vanadzina et al., 2019; Wamalwa et al., 2023). These models are increasingly shaped by end-user segmentation, sectoral priorities, digital technologies, and the need for flexible and inclusive revenue structures[20]. To capture this diversity and innovation, the discussion is structured into two parts: first, an examination of the structural foundations and delivery mechanisms of business models, and second, a

[20] While not a focus of the literature reviewed, carbon credits are increasingly recognised as a promising mechanism to enhance the financial viability of decentralised energy systems, with clean cooking leading current applications (Matsubara, 2024; Mawusi et al., 2025). Though still limited in the productive use space, emerging cases and advances in digital monitoring suggest growing potential, particularly where renewable technologies displace diesel or biomass in income-generating activities (Demidov et al., 2023; Tam et al., 2024).

discussion of innovative configurations, bundling strategies, and sector-specific differentiation.

Model structures and delivery approaches

Business models for delivering renewable energy for productive use in rural Africa are structurally diverse but they share a unifying logic: the need to balance financial viability with inclusive service provision in low-income, infrastructure-poor environments. These models are increasingly tailored to address structural constraints such as unpredictable demand, limited ability to pay, and weak institutional support while leveraging innovation in delivery modalities, technology integration, and user engagement.

A foundational insight across the literature is that successful models anchor energy systems in productive applications that stabilise demand and revenues. Several case studies demonstrate that coupling residential use with commercial and industrial demand enhances financial performance (Kyriakarakos et al., 2020). In Tanzania, hydropower-fed mini-grids serving a mix of household and productive use customers achieved higher income and load balancing, as only 25% of productive users contributed 44% of total income, largely due to productive operations like milling and welding (Hartvigsson et al., 2021). Similarly, in Cambodia and South Asia, rice mills serve as productive anchors in mini-grid models, significantly enhancing utilisation and cost recovery without requiring subsidies, especially when demands are complementary (e.g., off-peak mill use) (Bhattacharyya, 2014; Pode et al., 2015). Phased implementation, beginning with industrial clients and then extending service to residential users, proved cost-optimal in Burkina Faso, further supporting the case for diversified load structuring (Gül, 2021). These anchor-based strategies often intersect with broader development logics. The "KeyStarter" model in Nigeria and Kenya exemplifies this through backwards integration into agricultural value chains. By supporting upstream actors, such as farmers requiring inputs, developers stimulate demand, enhance energy use, and stabilise revenue (Sesan et al., 2024). In parallel, the "electrification seed" approach fosters bottom-up expansion by positioning local MSMEs or institutions as initial investors and demand hubs, allowing mini-grids to grow organically from viable starting points (Huber et al., 2021). Such integrative approaches reinforce the potential of energy systems not only as utilities, but as facilitators of wider rural economic transformation.

A notable structural shift in productive use delivery has been the transition from product-based sales to service-based models (P. Trotter, 2019). Models such as appliance leasing and productive equipment financing play a catalytic role in activating latent demand and improving load factors, especially in low-consumption environments (Gelchu & Ehnberg, 2024). However, such approaches depend on careful customer segmentation and load balancing to avoid technical strain or over-investment. In Rwanda, OffGridBox deploys modular containerised units that provide solar electricity, purified water, and connectivity services through a centrally operated, retained-ownership model. This design allows for consistent service delivery while blending donor co-financing with private investment (Miles et al., 2022). A similar logic underpins Pay-As-You-Go Business Energy (PAYG-BE) models piloted in Malawi, where entrepreneurs repay system costs over time (Smith et al., 2019). These models underscore the importance of aligning repayment mechanisms with income cycles and affordability.

The private sector has been particularly effective in advancing digital and customer-oriented business models. In Kenya, developers representing 87% of private mini-grids have sustained operations through value-creation strategies such as IoT-enabled smart meters, adaptive billing systems, and flexible pricing to align service delivery with users' ability to pay (Ogeya et al., 2025). This emphasis on tailored service provision is reinforced by evidence from Tanzania, confirming that user journey mapping can reveal mismatches between service expectations and actual usage, emphasising the need for differentiated value propositions across user segments (Ogeya et al., 2021). Similarly, solar home system models in Kenya and Bangladesh demonstrate that long-term sustainability depends as much on entrepreneurial drive and user-centric design as on initial capital, especially in markets dominated by informal economies and volatile incomes (Heinemann, 2022).

Community ownership models offer another structural alternative, often relying on grant-funded capital and community-led governance. In India, 24 solar mini-grids achieved financial and technical sustainability by engaging communities early, establishing Village Energy Committees, and ensuring consistent electricity supply, although productive use remained limited due to sociocultural constraints (Katre et al., 2019). A case from Sri Lanka similarly highlights the importance of clear policy direction, community management, credit access, and capacity-building for the successful implementation of off-grid micro-hydro systems (Sarangi et al., 2020). Yet, even where technical and organisational systems are sound, unrealised productive use potential remains a challenge. In contrast,

community energy initiatives in Ethiopia and Mozambique have struggled due to weak regulatory support, lack of targeted incentives, and limited awareness of viable business models, underscoring the critical need for institutional scaffolding (Gebreslassie & Cuvilas, 2023).

Hybrid system configurations further broaden structural possibilities. The Integrated Rural Energy Planning framework in Nigeria demonstrates how demand-side management and hybrid generation, particularly combining solar PV with biomass, can produce locally optimised, development-aligned systems (Ugwoke et al., 2020). In India, a solar-biomass hybrid microgrid was designed to overcome the limitations of low demand and difficult terrain, offering power for irrigation, commerce, and household use while ensuring cost-effectiveness (Singh & Balachandra, 2019). Meanwhile, in French Guiana, the integration of hydrokinetic energy with a triple-layered business model canvas and multi-criteria assessment tools ensured the alignment of environmental, social, and financial dimensions in remote rural electrification (Mallard et al., 2020).

Bioenergy models represent another structurally distinct category, decentralising production and embedding energy systems within local resource cycles. In 15 case studies across Latin America, Africa, and Asia, success was contingent on long-term planning, regulatory support, and cross-actor value chain collaboration (S. Hunt et al., 2012). These projects not only diversified rural incomes but also avoided trade-offs with food security by using biomass residues and complementary crops. Small-scale systems remain vulnerable to financing constraints, particularly due to high upfront costs and user hesitancy toward unfamiliar technologies. Flexible financing mechanisms such as PAYGo or lease-to-own schemes have proven effective in lowering these barriers, as shown in an assessment of 23 renewable energy projects globally (Terrapon-Pfaff et al., 2014). Even at the micro-enterprise scale, battery charging systems powered by biogas, requiring minimal capital, have demonstrated financial viability and rapid payback, offering scalable productive use options for low-resource entrepreneurs (Cherry et al., 2014). At the industrial scale, a recent study from Albania illustrates the technical and financial viability of biomass energy projects in olive oil processing, highlighting strong replication potential for other agricultural sectors (Shumka et al., 2021). It emphasises the need for market assessments, cost-effective technologies, informed financiers, and a coordinated national strategy. The case reinforces that scaling biomass for productive use requires not just technical feasibility, but targeted policy, sector-aligned financing, and institutional engagement.

Beyond delivery mechanisms, institutional frameworks play a crucial role in shaping model bankability. A comprehensive classification of Power Purchase Agreements (PPAs) reveals how standardisation can reduce transaction costs, clarify investor expectations, and facilitate adoption in contexts with diffuse or uncertain energy offtake (Mittler et al., 2025). In South Africa, legal and fiscal incentives such as tax credits, accelerated depreciation, and carbon finance have supported decentralised microgrid investments, contributing to higher project returns and investor interest (Nkambule et al., 2025). Complementing this, the World Bank's experience with PV dissemination, via both dealer and fee-for-service models, illustrates how public finance institutions can de-risk off-grid electrification, particularly in fragile or remote regions (Cabraal, 2012).

Across this landscape of business model architectures, a set of recurring structural principles becomes apparent: modularity, scalability, productive demand anchoring, financial flexibility, and institutional adaptability. The most resilient models are those that conceptualise energy not merely as a commodity, but as a service enabler embedded in local economies. By linking technical design with socio-economic development strategies, these models offer the most promise for scalable, investable, and inclusive electrification across Africa.

Innovation, bundling, and sectoral differentiation

As energy access efforts shift from achieving basic connectivity to driving local economic transformation, business models for productive use are evolving in both form and function. This evolution is marked by a decisive move toward innovation in service delivery, strategic bundling with complementary sectors, and context-sensitive differentiation (Falchetta et al., 2022; Garcia et al., 2024; Vanadzina et al., 2019). These shifts are not peripheral innovations; they are core to resolving the financial and operational constraints that have historically hindered the scalability of energy systems in rural, low-income environments. The literature increasingly reflects a transition from narrow, technology-first approaches toward integrated models that treat energy access as part of a wider socio-economic system (Gebreslassie et al., 2024; Patel et al., 2022; Wang, 2021).

A key insight is that bundling energy with productive services, particularly in agriculture, is critical to unlocking value. Integrated planning approaches that align mini-grids with irrigation, crop cycles, and value-added agri-processing have been shown to significantly reduce electricity unit costs and improve the financial viability of rural electrification (Falchetta et al., 2024; Raji et al., 2024; Wamalwa

et al., 2023). Models combining PAYGo financing with tailored load design allow smallholder farmers to access both energy and irrigation infrastructure, increasing profitability while stabilising mini-grid revenue. Similarly, in rice-milling contexts, self-sustaining biomass-powered models have emerged as effective subsidy-free solutions (Pode et al., 2016). By directly aligning energy production with agri-industrial demand and redistributing surplus electricity to nearby households, such systems generate stable anchor loads and reduce capital risk.

Several studies highlight how sectoral bundling can extend beyond agriculture to encompass cold storage (Garcia et al., 2024), healthcare (Imasiku & Saunyama, 2025), and connectivity services (Vanadzina et al., 2019). Off-grid solar PV cold chains serve diverse needs, including food preservation and vaccine storage, allowing operators to diversify income streams while addressing critical rural service gaps (Garcia et al., 2024). In the healthcare sector, electrifying off-grid clinics via blended finance mechanisms not only improves service delivery but also creates high social returns, making health facilities attractive anchor clients (Garcia et al., 2024). The Fusion Grid model illustrates the potential of pairing electricity with internet access to enhance digital livelihoods and investment appeal, demonstrating that multipurpose service delivery can lower unit costs and increase demand elasticity (Vanadzina et al., 2019).

Innovative digital tools are also shaping new business architectures. Quota-sharing mechanisms and blockchain-based peer-to-peer (P2P) energy trading enable decentralised systems to allocate power more efficiently, reduce energy waste, and improve revenue capture (Demidov et al., 2023). Likewise, the integration of Internet of Things (IoT) technologies into energy systems, exemplified by China's evolving energy sector, demonstrates how smart data tools can support remote monitoring, adaptive pricing, and user-centric service design, which are increasingly relevant in African contexts as systems decentralise (Wang, 2021).

Another layer of differentiation emerges in how business models adapt to sector-specific and contextual constraints. In Ethiopia, community energy systems have struggled under weak institutional frameworks and limited financial capacity, requiring hybrid cooperative models underpinned by revolving grant-seeded funds and targeted capacity-building (Gebreslassie et al., 2024). In contrast, experiences from India and the Philippines reveal the strength of business models that integrate clean energy provision with livelihood diversification and social enterprise strategies, fostering both income generation and long-term viability (S. S. Das et

al., 2022; Röder et al., 2020). This emphasis on embedding energy access within broader development logics also resonates in the context of urban informality. In Nairobi's Kibera settlement, a hybrid solar-battery mini-grid serving the Kibera Town Centre was optimised to cut energy costs by 60%, making it cheaper than grid tariffs (Patel et al., 2022). Building on this technical success, a "mini-grid franchise" model was introduced to enable local businesses and households to operate as franchisees, linking energy access with employment, supplemental income, and greater community ownership. This model demonstrates how decentralised energy systems can become both financially and socially viable in informal urban settings, provided they are grounded in participatory design and supported by enabling policy frameworks. Similarly, in the domain of clean cooking, a phased business model has been proposed that begins with public-sector investment and gradually transitions to private-sector-led expansion. Such an approach, grounded in socio-cultural awareness and local capacity, offers a practical pathway to overcome affordability barriers while maintaining long-term sustainability (Vassiliades et al., 2022). Building on this logic of public-private role sharing, a recent study from India proposes an evolved distribution franchisee model that integrates private mini-grid operators into utility-led distribution systems (Shrimali & Sen, 2020). In a context where near-universal grid electrification has challenged the scalability of standalone mini-grids, this model enables operators to manage generation, metering, billing, and maintenance within clearly defined partnerships. The arrangement offers internal rates of return above 12% for private firms while supporting public utilities in achieving 24-hour electricity access and renewable energy integration. Crucially, its success depends on transparent agreements regarding responsibilities and revenue-sharing mechanisms. Collectively, these cases highlight the critical importance of business model innovation tailored to local realities. To scale such innovations globally, some scholars argue for the establishment of a network of energy access innovation centres (Nathwani & Kammen, 2019). These centres would serve as dynamic extension platforms, linking technology development with on-the-ground implementation through capacity building, participatory design, and operational support.

Crucially, innovation is not confined to technology or product design; it includes financing architecture and investor alignment. Four promising strategies have been identified for unlocking private investment: anchor-business-community (A-B-C) models that stabilise demand; business models linked to income generation; engagement of local financial institutions familiar with market realities; and securitisation of distributed energy assets to attract institutional capital

(Falchetta et al., 2022). These mechanisms collectively point toward a maturing sector that must balance financial returns with social impact. Case studies such as Husk Power Systems further demonstrate that navigating tensions between affordability and sustainability in bottom-of-the-pyramid markets requires hybrid models capable of integrating socio-technical complexity into their design (Bandi et al., 2022). Importantly, the viability of productive use models depends not only on initial financing but also on long-term enterprise durability. A study in Madagascar shows that productive users, often treated as anchor customers, can jeopardise system sustainability if they cease operations (Schöne et al., 2024). Therefore, ownership structures, community involvement, and enterprise support mechanisms must be designed to sustain productive demand over time.

Across this diverse spectrum, successful models share three traits: they integrate energy with sectoral demand; they adopt flexible, phased, or hybrid financing strategies; and they foster innovation that aligns technology, behaviour, and context. As such, innovation in business models is no longer about novelty for its own sake, it is a strategic imperative for delivering sustainable, scalable, and socially embedded productive use systems across Africa's rural and peri-urban landscapes.

8.3.2.3 Access to finance

The financial architecture surrounding productive use of energy remains fragmented and uneven, with access to capital persistently cited as a key barrier to scaling energy solutions that go beyond household electrification (Ogunjuyigbe et al., 2024; Yamegueu et al., 2019). While technological readiness has improved and business models have diversified, financing structures have not kept pace with the nuanced needs of capital-intensive, revenue-generating productive use projects (Chirambo, 2021; Crevani et al., 2023). Across the literature, a common thread emerges: viable productive use systems require not only access to funds but also alignment between financial and policy instruments, project design, user capacity, and long-term sustainability goals (Pachauri et al., 2024; P. A. Trotter & Brophy, 2022). Recent evidence signals a shift away from one-size-fits-all solutions toward a more layered financial ecosystem, one that includes microfinance, concessional lending, commercial capital, project finance, and blended finance structures, all tailored to local market conditions and use cases (Bose, 2011; Mbate & Fall, 2025). However, this evolving financial landscape remains constrained by mismatches between risk perception and actual project performance (Duppati et al., 2025), underdeveloped local financial markets (Du et al., 2025; Mbate & Fall, 2025), and

institutional asymmetries between donors, governments, investors, and communities (Duppati et al., 2025; Tarekegne & Sidortsov, 2021). In response, the literature calls for adaptive financing strategies that match capital structure to end-user realities, integrate technical and demand-side planning, and build the financial capabilities of both developers and consumers (Crevani et al., 2023; Kagimu & Ustun, 2016; Kouassi & Pineau, 2011). The following three subsections explore this landscape in depth: the first focuses on core financing instruments and innovations; the second on enabling demand through end-user finance and affordability mechanisms; and the third on the policy and institutional ecosystems required to support sustainable investment at scale.

Financing instruments: From debt and equity to blended and concessional models

Investments in productive use projects, specifically in sub-Saharan Africa, face distinct capital structure challenges. Project-level financial engineering has become increasingly critical as developers navigate high upfront costs, uncertain demand, and long payback periods. Several studies emphasise the role of tailored debt and equity mechanisms, including microfinance, concessional loans, and project finance, to bridge the financing gap for both developers and end users.

Microfinance has shown promising results in rural contexts where traditional bank credit is inaccessible. In Burkina Faso, solar water pumping systems (SWPS) for irrigation became economically viable for medium- and large-scale farmers through tailored microloans at 9.5% interest (Yamegueu et al., 2019). However, the study also stresses the importance of matching finance to operational realities: for example, integrating diesel backup pumps for cloudy days proved more cost-effective than solar-powered storage. Similarly, in Nigeria, access to credit for microenterprises significantly increased their willingness to adopt renewable energy systems, particularly when these included storage to ensure reliability (Ogunjuyigbe et al., 2024). Emerging literature further underscores the importance of localised, user-centric financial models. Locally led innovations, such as bundling, community-driven ownership, and embedded PAYGo systems, can improve affordability, reduce transaction costs, and build investor confidence when paired with grant or concessional capital (Pachauri et al., 2024).

On the developer side, project finance emerges as a crucial structure for de-risking mini-grid investments. A case study from Mozambique illustrates how incorporating realistic debt-equity structures into energy planning models

significantly improves both technical design and bankability (Crevani et al., 2023). Project finance facilitates access to international capital, allocates risk efficiently, and enables longer-term investment horizons, key advantages in a sector plagued by short funding cycles and donor-driven volatility. Standardisation also plays a critical role. In response to persistent project-level customisation, a proposed rural electrification scheme recommends structured development pathways aligned with the UN Sustainable Energy for All (SE4ALL) service tiers, aiming to reduce transaction costs, clarify risks, and attract investors (Kagimu & Ustun, 2016). This approach builds on the understanding that replicability and predictability, especially in financial planning, are essential for scaling. Yet financing gaps persist, particularly for early-stage enterprises and high-CAPEX deployments. Several scholars call for more private sector involvement, recognising that donor and government funds alone cannot meet investment needs. Innovative financing vehicles, such as dedicated clean energy investment funds, are needed to channel risk-tolerant capital toward unproven but high-impact models (Chirambo, 2021). One such approach is the financial gradient model, which offers a structured framework for stabilising funding flows by blending public, philanthropic, and commercial capital into phased, de-risked investment stages (Bose, 2011). This model provides a strategic pathway to mobilise diverse financing sources while managing risk exposure across the project lifecycle, particularly relevant for productive use investments that require long-term commitment and adaptive capital structuring. However, this will require stronger domestic financial markets and more equitable governance structures. As critics of electrification efforts argue, misaligned incentives and power asymmetries between African stakeholders and international financiers often undermine local ownership and project longevity (Kouassi & Pineau, 2011).

Ultimately, these studies converge on a shared insight: financing productive use is not just about unlocking capital, but about aligning financial instruments with operational models, governance structures, and user realities. Hybrid financing strategies, those that blend microfinance, project finance, and donor support, offer the most promising pathways to scale, particularly when combined with planning tools that internalise risk, affordability, and long-term sustainability.

Enabling demand: Subsidies, appliance access, and financial inclusion

Stimulating end-user demand is a core condition for the financial viability of productive use of energy systems, especially where baseline electricity consumption is low. A growing body of evidence emphasises that demand cannot

be decoupled from affordability and that financing mechanisms must go beyond infrastructure investment to include appliances, complementary services, and inclusive access to capital (Husein et al., 2024; Lukuyu et al., 2021; Mbate & Fall, 2025).

Subsidising productive use equipment, rather than infrastructure alone, is consistently shown to be the most cost-effective strategy. In Nigeria, geospatial modelling across nearly 23,000 population clusters confirmed that among concessionary loans, capital subsidies, and appliance financing, it was the latter, financing income-generating appliances, that most significantly reduced the levelised cost of electricity (LCOE) and improved project viability (Husein et al., 2024). National programmes such as the Energising Agricultural Programme and the Result-Based Financing for Productive Appliances have supported this approach, with many financed appliances reaching payback within one year. Similarly, in East Africa, a study across 29 villages found that appliance financing led to a 66% increase in electricity consumption among mini-grid users (Lukuyu et al., 2021). However, this effect was temporary and weakened by incomplete repayment rates, highlighting the fragility of credit-based schemes when not supported by robust repayment mechanisms. Tariff subsidies, offering reductions of up to 75%, also boosted consumption but delivered mixed results in terms of overall revenue retention. These findings underscore that in mini-grid business models where financial sustainability depends heavily on energy demand, stimulating usage is essential, but it must be coupled with carefully designed affordability mechanisms and safeguards to ensure long-term viability.

Strategic subsidy allocation further amplifies viability in multi-service applications. In Niger, directing investment subsidies specifically to the PV and battery components of an integrated solar-water system reduced electricity costs by nearly 80% (Kuckshinrichs et al., 2025). This case highlights how targeting subsidies to the most capital-intensive components, rather than evenly across the system, yields greater cost reductions and aligns with community preferences. Similarly, in Rwanda's Nyabiheke refugee camp, hybrid mini-grids improved financial performance and emissions outcomes compared to diesel-based systems, especially when paired with productive loads and when planning strategies aligned with donor funding cycles (Baranda Alonso et al., 2021).

More fundamentally, financial inclusion operates as an underlying enabler. Hybrid models that integrate financial and technological functions, such as financial institution-technology provider partnerships or PAYGo platforms, can reduce

upfront barriers and mobilise capital for productive use solutions (Patrick Reichert & Umberto Trivella, 2015). However, their success hinges on strong operational support, quality control, and suitability for high-load applications. In Kenya, analysis of household survey data showed that both formal and informal financial institutions, as well as digital platforms, substantially improved energy access by easing liquidity constraints, enabling staggered payments, and reducing transaction barriers (Mbate & Fall, 2025). Strengthening these systems, particularly informal savings groups, can unlock access for households and MSMEs that are otherwise unable to meet traditional credit requirements.

Macroeconomic policy, particularly monetary policy, also plays a critical, yet often underappreciated, role in shaping the enabling environment for electricity demand (Du et al., 2025). Expansionary monetary interventions, such as increasing the money supply or easing interest rates, can lower the cost of capital and stimulate investment in modern energy services. These macro-level tools operate through channels including increased liquidity, enhanced credit availability, and reduced energy price volatility. While such policies have improved electricity access in many developing regions, their effects are not uniform; in sub-Saharan Africa, structural economic constraints have limited positive outcomes. Nevertheless, the study underscores the potential for central banks to directly support energy access and productive use projects by offering low-interest financing for renewable technologies, targeting investment toward low-income groups, and implementing inflation-sensitive pricing policies. These measures can strengthen the financial viability of productive use models by improving users' purchasing power and willingness to adopt modern energy services, thereby reinforcing the effectiveness of micro-level interventions such as appliance subsidies and inclusive credit schemes.

Together, these studies demonstrate that enabling demand requires an integrated strategy, one that combines direct financial tools like subsidies and appliance credit with institutional enablers such as financial inclusion, macroeconomic alignment, and adaptive business models. In the absence of such mechanisms, even well-designed infrastructure may remain underutilised. Demand is not a given; it must be financed, supported, and embedded in broader social and financial systems to unlock the full potential of productive use of energy.

Policy institutions and investment ecosystems

The financial viability of productive use of energy initiatives is deeply intertwined with the quality of enabling policies, institutional arrangements, and broader investment ecosystems. These factors not only shape project bankability but also influence long-term sustainability and equity outcomes. A recurring insight across the literature is that finance alone is insufficient; successful project deployment requires coherent policy frameworks and institutional scaffolding that align with local socio-economic conditions (Barnes, 2011; Tarekegne & Sidortsov, 2021; P. A. Trotter & Brophy, 2022).

Grid integration policies play a pivotal role in sustaining donor-funded or aid-based energy systems. A case from Bangladesh (Yi & Kim, 2025) shows how surplus electricity from off-grid PV systems can be fed into the grid through mechanisms like net metering and feed-in tariffs. These options allow for partial cost recovery, especially for O&M, ensuring that once-electrified communities remain served post-grid arrival. Without such measures, well-intentioned aid investments risk obsolescence as soon as national infrastructure expands. In parallel, large-scale public financial flows, particularly through official development assistance (ODA), are increasingly aligned with renewable energy financing, especially for solar and bioenergy in Africa (Nsakaza & Chilipaine, 2025). Instruments like securitisation and blended finance are recommended to unlock private investment by converting future revenue streams into investable financial products. Yet, the effectiveness of these tools depends on robust policy ecosystems that ensure transparency, predictable repayment structures, and long-term strategic alignment. At the same time, regulatory incoherence can significantly undermine energy access investments. In Tanzania, for example, policy mandates enforcing tariff parity between subsidised grid electricity and unsubsidised mini-grid power have placed undue pressure on private developers (Maqelepo et al., 2025). These mini-grids, which operate on fundamentally different cost structures, are left with two suboptimal options: maintaining full reliability and incurring financial losses or limiting supply to maximise profit. The latter approach, while more profitable, can reduce service reliability to around 92% or lower, diminishing user trust and satisfaction. The study highlights how such policies may inadvertently drive private operators out of the market, threatening the sustainability of rural electrification and undermining progress toward SDG 7.

The role of government spending also emerges as a critical enabler. A study across 31 developing countries finds that public investment is more consistently

effective in alleviating energy poverty than financial development or market expansion alone (Ashena & Shahpari, 2025). This underscores the need for state leadership in building foundational energy infrastructure, especially where private returns are uncertain. Additionally, policies that foster economic complexity, through industrial diversification and value chain upgrading, can improve the viability of investments in productive use projects by strengthening the productive use base and creating demand for modern energy services. Still, finance must be accompanied by conducive institutional conditions. In Africa, many green finance initiatives are too small, fragmented, or administratively burdensome to attract serious private interest (Duppati et al., 2025). Without strong demand signals, adequate infrastructure, or streamlined approval processes, investment flows remain constrained. Moreover, green finance's positive impact on energy access is strongest during recessions or in low-income, low-capacity contexts, further highlighting the need for macro-policy alignment and robust institutional support (Sultanuzzaman et al., 2024).

To foster innovation, supportive policy mixes must balance targeted incentives with regulatory oversight. Drawing on evidence from six African countries, one study outlines how policies that coordinate across sectors and scales can enable business model innovation (P. A. Trotter & Brophy, 2022). Productive tensions, such as between rural development goals and cost-recovery imperatives, can catalyse new approaches if managed constructively. Similarly, rigid, one-size-fits-all electrification models are inadequate; rather, institutional adaptability, through dedicated rural agencies or embedded programmes within utilities, is critical to serve dispersed, low-income populations (Barnes, 2011).

Beyond macro-institutional dynamics, energy justice considerations are gaining importance. DFIs often rely on standard appraisal criteria that overlook distributive and procedural equity (Tarekegne & Sidortsov, 2021). As a result, well-funded projects may reinforce existing disparities if they fail to account for the capabilities and lived realities of marginalised users. Embedding justice principles in financing and planning frameworks is essential to ensure that productive use systems enhance livelihoods and social inclusion, not just access metrics or investor returns.

Across all these contributions, one message is clear: enabling environments are not abstract; they must be actively constructed through policy, public investment, and institutional innovation. Without them, even well-financed and technically sound initiatives fostering productive use may fail to reach scale or impact.

8.3.2.4 Risks and enabling conditions

The financial and operational sustainability of productive use of energy systems is shaped not only by access to capital and technology but by the broader landscape of risks and enablers within which they unfold. In many low-income or remote contexts, even well-financed and technically sound initiatives can falter if they encounter systemic constraints, ranging from regulatory instability and governance failures to underdeveloped markets and infrastructure gaps (Bukari et al., 2021; James et al., 2025; Kapole et al., 2023; Lambe et al., 2024; Peters et al., 2019). Conversely, where enabling conditions exist, such as adaptive policy frameworks, demand-aligned business models, and community co-ownership, projects are more likely to deliver lasting economic and social impact (Baldwin et al., 2015; Mosetlhe et al., 2025). To unpack this complexity, the literature reviewed in this section is organised into two subsections. First, external risks are examined, those stemming from policy incoherence, macroeconomic volatility, institutional fragmentation, and misaligned incentives, which affect the broader investment ecosystem. These risks often distort cost recovery, deter private capital, and weaken long-term viability even when basic energy infrastructure is in place. This is followed by exploring internal risks, in other words, the challenges emerging from within the energy system itself, such as demand shortfalls, seasonal productive loads, poor business model design, and weak user engagement. While these may appear localised, they often reflect deeper structural failures in project planning and implementation (van Hove et al., 2022; Zerriffi, 2008).

Notably, enabling conditions are not passive backdrops, they must be actively constructed. Effective de-risking strategies combine blended finance with strong institutions, inclusive planning, and targeted demand stimulation (Fajardo et al., 2025). As such, addressing both external and internal risks is not only essential for attracting investment but also for ensuring that productive use systems achieve their full socio-economic potential (Mbazima & Lemaire, 2025; van Hove et al., 2022).

External risks

Productive use initiatives, particularly those reliant on decentralised systems such as mini-grids and distributed generation, face a complex array of external risks that shape their financial viability and long-term sustainability. These risks, ranging from policy instability and regulatory misalignment to weak demand signals, capital scarcity, and poor institutional coordination, can derail otherwise technically sound projects (Fajardo et al., 2025). Unlike internal risks, which stem from project design

or operations, external risks are embedded in the broader ecosystem: macroeconomic trends, political dynamics, land and licensing regimes, and investor confidence all play critical roles.

A recurring risk in decentralised energy deployment is the misalignment between national policy frameworks and the financial realities of mini-grid operations. In Ghana, for example, a policy of rigid tariff uniformity, designed to promote social equity, undermines the financial sustainability of mini-grids, which must operate without access to the cross-subsidies available to the national grid (Bukari et al., 2021). This creates a structural disincentive for private investment, despite the recognition that mini-grids represent the most cost-effective option for electrifying remote areas. According to this study, political, economic, and technical barriers together account for 70% of the constraints facing the sector, with access to finance ranked as the most critical. In addition to unattractive tariff structures, the study identifies low levels of productive electricity use, weak private sector participation, unclear policies, and underdeveloped business models as key impediments. Without targeted policy reforms and a coherent investment framework, mini-grid deployment in Ghana is likely to remain stalled, despite its technical viability and alignment with rural electrification goals. Such dynamics are not unique to Ghana. Throughout sub-Saharan Africa and beyond, distributed generation systems, whether donor-funded, privately operated, or community-based, struggle to achieve scale and durability in the absence of enabling frameworks (Baldwin et al., 2015). Market-based approaches, such as those relying on microfinance or bulk procurement, have emerged as alternatives to public sector-led models, yet they too falter without robust demand, policy clarity, or institutional support. Many systems remain locked in a cycle of pilot projects and partial deployments, a consequence not of poor technology but of systemic governance and coordination gaps.

Regulatory incoherence also manifests in more subtle but consequential forms. In Ghana, inconsistent or overlapping mandates, weak land tenure systems, and limited technical capacity within government agencies contribute to permitting delays and elevated transaction costs for renewable energy developers (James et al., 2025). These inefficiencies increase perceived risk, deter private capital, and raise the cost of finance, ultimately undermining the economic viability of energy access initiatives. A Delphi-based assessment of 44 barriers ranks policy, institutional, and financial constraints as the most significant, including unclear regulations, lack of market incentives, high interest rates, and limited political commitment. The study calls for market-based policy reforms, land tenure restructuring, and institutional

strengthening to accelerate renewable energy uptake. Case studies from Kenya highlight the consequences of failing to navigate these conditions (Lambe et al., 2024). Private-sector mini-grid operators aiming for rapid scale found their business models unravelled in the face of political interference and unmet demand projections. Attempts to diversify electricity consumption into agribusiness or electric mobility failed when technologies mismatched local conditions or when regulatory frameworks offered no protection against competition from future grid expansion. Indeed, the threat of grid encroachment is among the most significant unpriced externalities affecting investments in energy access initiatives (Williams et al., 2015). Mini-grids deployed in unserved regions often face the risk of being stranded if the central grid eventually arrives, especially in the absence of integration mechanisms or compensation schemes. Despite widespread recognition of this problem, few countries have established policy instruments such as demand guarantees, risk-sharing tools, or clear frameworks for grid interconnection. This persistent policy vacuum heightens uncertainty and discourages long-term financing.

The literature also reveals how knowledge asymmetries and limited cross-project learning reproduce these risks. Fragmented research, donor-driven evaluation incentives, and a lack of systematic assessment make it difficult to understand what works, and why, in different settings (Schäfer et al., 2011). As a result, business models are often transplanted across contexts without adequate adaptation, leading to repeated implementation failures. Without transparent feedback mechanisms and embedded learning processes, financing strategies are prone to replicate earlier mistakes, ignoring the socio-technical complexity of energy access systems (Zerriffi, 2008).

In short, external risks to investments in energy access are not incidental, they are systemic. They manifest through the absence of effective institutions, the politicisation of pricing and planning decisions, and the failure to create coherent, transparent, and adaptive regulatory environments. While some promising de-risking mechanisms exist, the literature consistently underscores the need to move beyond narrow project interventions. Addressing external risks requires coordinated policy reform, institutional innovation, and a restructuring of energy governance that puts productive use at the centre of rural electrification strategies.

Internal risks

Even where enabling environments exist, the internal dynamics of productive use systems present a suite of challenges that can compromise financial viability and long-term sustainability. While much attention has been devoted to overcoming external barriers to rural electrification and productive use, internal risks, those embedded in system design, user behaviour, financing structures, and demand characteristics, remain equally critical. These risks are particularly pronounced in sub-Saharan Africa, where rising access rates have not translated into adequate levels of electricity consumption or productive use. Across the literature, three cross-cutting themes emerge: the persistent gap between access and demand (Lukuyu & Taneja, 2023), the misalignment between productive use load profiles and energy system design (van Hove et al., 2022), and the challenge of creating adaptive, community-responsive business models that remain financially viable under low-income conditions (Pailman et al., 2024; Scott, 2017). These factors, if unaddressed, can undermine the long-term bankability and socio-economic impact of investments in productive use projects.

A persistent risk is that electrification does not lead to meaningful consumption or income-generating activity. In many rural contexts, demand for electricity, especially for productive purposes, remains too low or irregular to ensure financial sustainability. The review by (Lukuyu & Taneja, 2023) highlights that electrification strategies often over-rely on infrastructure roll-out while neglecting the demand-side enablers required to make systems viable. Appliance financing, targeted subsidies, and the promotion of electricity-based enterprises have shown some promise in stimulating demand, but their success depends on strong policy and institutional support. Without this, infrastructure sits underutilised, revenue remains weak, and systems fail to recover costs.

The challenge is compounded by overly optimistic demand forecasts, particularly for productive loads. Evidence from rural mini-grids in developing countries shows that both commercial and community-operated systems frequently fail to scale or sustain operations due to unrealistic projections, high payment default rates, and underestimated transaction costs (Peters et al., 2019). When policy frameworks fail to ensure cost recovery, either through reflective tariffs or stable subsidies, internal viability is further compromised.

Aligning electricity supply with productive demand profiles also presents a critical internal risk. Evidence from Sierra Leone indicates that mini-grids serving

residential users with some productive use integration fail to significantly improve financial viability unless productive loads are stable throughout the year (van Hove et al., 2022). Seasonal uses result in excess capacity during off-peak periods, inflating infrastructure costs without proportional gains in income. Similarly, techno-economic models from off-grid island communities show that linking electricity provision to consistent productive activities can improve project returns, but only when accompanied by well-designed policy incentives and flexible tariffs (Lozano et al., 2021).

Some studies emphasise that productive use systems must be anchored in existing or emerging economic structures to be viable. The "KeyMaker" model, discussed by Mosetlhe et al. (2025) provides an example of how microgrids can generate a third income stream by linking energy provision to value-added activities. In contrast, bottom-up models begin with current community livelihoods, such as aquaculture, small-scale manufacturing, or community services, and build energy systems around them. While the former creates new enterprise opportunities, the latter reduces risk by aligning with proven local demand. Combining both approaches may offer a balanced strategy, but success depends on user co-design, adaptive regulation, and blended financing mechanisms. Social and institutional dynamics further shape outcomes. In Zambia, anchor-based mini-grids, often promoted for their financial stability, can falter without reliable off-takers or enabling regulation. Even with strong anchor clients, broader revenue diversification and regulatory clarity are needed to attract private capital and ensure long-term viability (Mbazima & Lemaire, 2025). In India, evidence from grid-connected rural areas shows that mini-grids operating in parallel to the main grid are financially viable primarily when they serve non-farm enterprises with a high need for reliability (Sharma et al., 2020). However, in the absence of complementary infrastructure or business development services, demand growth remains limited and system-level returns are constrained.

Planning, operations, and subsidy design are equally critical to internal system performance. Mini-grids in Zambia failed to recover costs due to poor component quality, unaffordable tariffs, and the absence of structured business models (Kapole et al., 2023). Public-private partnerships may help resolve these issues, but only if subsidies are smartly structured to align investor and user incentives. Likewise, successful financial models depend not only on recovering capital costs but also on ensuring ongoing technical support and institutional continuity.

Finally, internal risks are particularly acute in informal urban areas where residents often live and work outside formal systems. The Umbane project in Cape Town illustrates how conventional financing and delivery models are poorly suited to such environments (Pailman et al., 2024). Instead, flexible, community-led microgrid initiatives that engage end users, especially women-owned enterprises, can better match local needs and conditions. These findings emphasise that internal viability hinges not only on technical design but also on socio-economic fit, affordability, and participatory implementation. Complementing this, a second study identifies four essential elements for successful decentralised energy initiatives in marginalised settings: meaningful community engagement, strategic partnerships, local capacity development, and the deliberate navigation of structural barriers, including limited financing channels, low education levels, and weak distribution infrastructure (Scott, 2017).

Together, these studies reveal that internal risks to productive use projects are multifaceted and context-specific. Mitigating these risks requires a shift from top-down electrification approaches to integrated strategies that pair energy provision with demand stimulation, inclusive business models, and localised support systems. Only then can investments in energy access deliver durable returns and inclusive development outcomes.

In sum, the reviewed literature underscores that successful delivery and financing of productive use energy systems hinge not only on technical soundness or financial innovation, but on their fit within broader institutional and socio-economic ecosystems. Models that thrive in one setting may falter in another if enabling conditions are misaligned. This reinforces the need for context-sensitive approaches, ones that translate theoretical frameworks into empirically grounded strategies. The next section turns to this task, using detailed enterprise-level data from the six African case studies to identify how specific business models and financing mechanisms might be tailored to support clean energy transitions in diverse enterprise and policy environments.

8.3.3 Case study assessment: Matching models to case studies

The previous section synthesised insights from the literature on business model structures, financing instruments, and systemic risks shaping the deployment of decentralised energy solutions. Yet translating these insights into actionable strategies for women-owned enterprises requires close attention to the institutional terrain in which such models must operate. This section turns to a comparative

analysis of six African countries to examine how energy performance outcomes, financing needs, and gender equity objectives interact with national enabling environments.

Before exploring each case study in detail, it is critical to contextualise the feasibility of proposed business models and financing mechanisms within country-specific institutional conditions. Table 35 provides a comparative snapshot of the enabling environment across the six countries, drawing on reputable datasets, including the World Bank's now-discontinued Ease of Doing Business index (2020), the new Business Ready report (2024), the AfDB's ERI (2022), and the World Economic Forum's Global Gender Gap Index (2024). Together, these indicators offer a diagnostic lens for understanding the structural conditions likely to influence model uptake, investment risk, and gender-responsive delivery at scale.

Across the sample, institutional readiness is generally moderate, with considerable variation in regulatory maturity, administrative capacity, and gender equality performance. Notably, no country in the dataset achieved a performance score classified as "high" (above 80 or 0.800) on any of the composite indices, suggesting that while enabling frameworks exist, they remain partial and uneven, often requiring targeted reinforcement to support inclusive, decentralised energy interventions.

Ghana, Kenya, and Tanzania demonstrate relatively acceptable enabling environments. All three receive "substantial" ratings in the ERI, indicating well-developed regulatory mandates and moderate to good implementation capacity. Their scores in the Global Gender Gap Index (0.701-0.734) also suggest a minimum institutional commitment to gender equity, though significant disparities remain. Ghana's regulatory framework scores relatively high (ERI: 66.91), but its public service delivery lags (47.67), potentially undermining programme implementation. Tanzania stands out for combining strong regulatory substance (ERI: substantial) with higher operational efficiency (62.15), even though its Ease of Doing Business ranking (141) indicates broader bureaucratic inefficiencies.

Nigeria represents the most constrained context, with a "low" ERI rating, a weak Doing Business score (56.9), and the lowest gender parity index among the sample (0.650). These indicators point to deep-seated institutional challenges that could limit the viability of decentralised business models unless explicitly mitigated through risk-sharing, targeted subsidies, or donor-backed technical assistance.

Tunisia and Malawi, by contrast, suffer primarily from data gaps rather than weak performance. Tunisia's moderate Ease of Doing Business ranking (78) and mid-range gender score (0.668) suggest potential for private sector engagement, but the absence of ERI and Business Ready data precludes a full regulatory assessment. Malawi's "substantial" ERI rating is promising, yet a lack of disaggregated gender and regulatory metrics limits comprehensive interpretation.

Taken together, these enabling environment indicators serve a dual purpose: first, as a foundation for cross-country differentiation in the analysis of business model suitability; second, as a reality check on the degree of institutional support available for scaling gender-responsive energy solutions. Countries with stronger regulatory performance and gender parity scores may offer a more coherent policy and institutional framework for supporting inclusive energy access models. Conversely, lower-scoring countries may require greater reliance on concessional finance, external risk mitigation tools, or bespoke institutional support mechanisms.

Table 35. Quantitative assessment of enabling environment conditions across case study countries

Country	Ease of Doing Business (2020)		Business Ready (2024)			ERI (2022)	Global Gender Gap Index (2024)	
	Rank	Score	Regulatory framework	Public services	Operational efficiency		Rank	Score
Ghana	118	60.0	66.91	47.67	54.42	substantial	88	0.701
Tunisia	78	68.7	n/a	n/a	n/a	n/a	115	0.668
Kenya	56	73.2	n/a	n/a	n/a	substantial	75	0.712
Malawi	109	60.9	n/a	n/a	n/a	substantial	n/a	n/a
Nigeria	131	56.9	n/a	n/a	n/a	low	125	0.65
Tanzania	141	54.5	65	51.56	62.15	substantial	54	0.734

Notes: The colour coding applied in this table follows the classification used in the ERI and has been extended across all indicators for consistency. For metrics on a 0-1 scale, scores between

0.800-1.000 are shown in green (high performance), 0.600-0.799 in yellow (acceptable/substantial performance), 0.500-0.599 in orange (moderate performance), and below 0.500 in red (weak performance). For indicators on a 0-100 scale, the same thresholds apply proportionally: 80-100 (green), 60-79.9 (yellow), 50-59.9 (orange), and below 50 (red). White cells indicate that data was not available or the country was not covered by the corresponding index.

With this comparative backdrop in place, the following subsections present the detailed results for each of the six country case studies, beginning with Ghana and proceeding in the order established by the scenario configurations. Each case is structured around three dimensions: (1) scenario context and energy access performance, (2) enabling environment, and (3) business model and financing strategy, including key recommendations and implementation gaps. This approach ensures consistency across cases while retaining the flexibility needed to reflect the unique conditions and opportunities of each national context.

8.3.3.1 Case study 1: Fish processing in Ghana

Case study 1 represents an NGO-led fish processing enterprise in Ghana categorised under ISIC Division 10 (Manufacture of food products), undergoing a transition to cleaner and more sustainable energy technologies. The initiative is motivated by the need to replace traditional fish smoking methods, which pose serious health and environmental risks due to high emissions and PAHs. The analysis explores three distinct enhancement scenarios, each offering potential pathways to modernise energy use. The findings offer a valuable entry point for applied research and collaborative implementation with local partners, emphasising the importance of inclusive design, affordability, and the capacity to adapt and scale within similar contexts.

Scenario context and energy access performance

Central to all three enhancement scenarios of case study 1 is the adoption of a low-cost, pre-smoking greenhouse dryer. This technology improves hygiene, reduces post-harvest losses, and enhances energy efficiency, providing a feasible entry point for modernisation without overburdening the NGO's capacity. The three enhancement scenarios differ primarily in their approaches to energy supply. Scenario 1 integrates solar PV under a net metering arrangement for electrical needs, paired with LPG for thermal energy. Scenario 2 explores full energy autonomy through solar PV and battery storage, with sub-options comparing lead-acid and lithium-ion systems. Scenario 3 shifts focus to environmental sustainability, replacing LPG with coconut husk-fuelled FAO-FTT kilns, a locally

sourced renewable biomass option. Electrical needs in this scenario vary between solar PV plus batteries and a net-metered configuration.

From an energy access standpoint, all three scenarios yield improvements in the MTF, with 2-3 tier upgrades, resulting in a final tier score of 4 in scenarios 1 and 2, and tier 3 for scenario 3. Notably, none of the scenarios report issues with energy availability or reliability, highlighting technical adequacy across configurations. CAPEX estimates range from 2,000 to 9,000 USD, depending on the system, with annual operating costs varying from 500 to 1,000 USD/year. Environmental gains are particularly strong under scenario 3, which achieves avoided GHG emissions of 5 $tCO_{2\text{-}eq}$/year. This suggests a viable trade-off between cost and sustainability depending on energy source selection.

Ghana's national business and financing landscape reinforces the feasibility of such interventions. According to the 2020 Ease of Doing Business ranking, Ghana scores 60 (ranked 118 out of 190 globally) (The World Bank Group, 2020). Its 2024 Business Ready scores indicate moderate strength in regulatory frameworks (66.91), but weaker performance in public services (47.67) and operational efficiency (54.42) (The World Bank Group, 2024a). The 2022 ERI further classifies the country's regulation as "substantial", indicating a relatively advanced level of development and implementation of electricity sector regulations, though with room for further alignment with international best practices (AfDB Group, 2022). On gender indicators, Ghana ranks 88 on the Global Gender Gap Index (2024), with a score of 0.701 (World Economic Forum (WEF), 2024), reflecting moderate progress toward gender parity across key dimensions but highlighting ongoing disparities that require policy attention. Although gender-focused support schemes exist on paper, practical implementation remains uneven.

Enabling environment: Policy, institutional and financial dimensions

Ghana's energy policy architecture is comparatively advanced, anchored by the Strategic National Energy Plan (SNEP 2019), which targets universal access by 2025 (GOGLA, 2021a). While this target has already been delayed, the plan offers long-term direction. The Renewable Energy Master Plan (REMP 2019) reinforces this by introducing technology-specific targets and fiscal incentives such as tax

exemptions for renewable energy components. However, policy fragmentation and delayed execution persist.

Institutions like the Ghana Energy Commission and the Ministry of Energy play central regulatory roles, but operational bottlenecks remain, especially in aligning clean cooking and off-grid electrification policies (Institute of Statistical et al., 2020). Although LPG promotion has historically been supported through cylinder distribution and subsidies, its rising cost burden poses challenges for NGOs. In this case, the use of LPG (scenarios 1 and 2) raises affordability concerns: while the government supports fuel availability, the cost is prohibitive for both the NGO and its base-of-pyramid clients. Higher processing costs may be passed on to consumers, undermining accessibility.

Off-grid and solar PV adoption is supported through programmes like Ghana Energy Development and Access Project (GEDAP) and the Scaling-up Renewable Energy Programme (SREP), which offer concessional finance and technical support (GOGLA, 2021a; Korzhenevych & Owusu, 2021). While Ghana's local content regulations, such as the requirement for 51% Ghanaian ownership and 60% local inputs, are designed to promote domestic economic participation and value creation, they may also pose challenges for attracting foreign investment by limiting flexibility in ownership and sourcing structures (GOGLA, 2021a). Tax exemptions for solar products are inconsistently applied, reducing investor predictability. The Solar Industry Association has made strides in advocacy and coordination, but limited institutional reach and implementation delays dilute its impact.

The financial landscape presents further constraints. Access to affordable finance is structurally limited by high interest rates (25-40%), short loan durations, and currency volatility (GOGLA, 2021a). Most energy loans are denominated in USD, exposing borrowers to macroeconomic risk and undermining external financing efforts. While impact investors such as Wangara Green Ventures and local banks (e.g., Ecobank, CalBank, Stanbic) provide some funding channels, uptake remains low due to collateral and repayment requirements. Programmes like GEDAP and REACT household solar have piloted collaborative financing models with rural banks, offering some momentum for inclusive end-user finance, including women-owned businesses.

Despite formal commitments to gender equity in Ghana's energy landscape, implementation remains uneven and limited in transformative impact. National policies such as the 2010 National Energy Policy and the Ghana Shared Growth

and Development Agenda (GSGDA) acknowledge the pivotal role women play in energy use and management, particularly in biomass and renewable energy, and commit to mainstreaming gender in planning processes (Asibey et al., 2021; Schiffer & Yesutanbul, 2021). Yet, these commitments have struggled to materialise into operational frameworks, especially in rural areas where institutional coordination is weaker. Similarly, while the Renewable Energy Master Plan (REMAP 2019) includes broad equity goals, it lacks clear pathways to operationalise gender inclusion (Schiffer & Yesutanbul, 2021). While the establishment of a gender focal point in the Ministry of Energy and the completion of a gender audit signal progress, the absence of similar structures at agency level has constrained the systemic uptake of gender-sensitive programming across the sector (Economic Community of West African States (ECOWAS), 2017).

This gap between policy intention and ground-level implementation extends to enterprise support programmes. The Programme for Sustainable Economic Development (PSED), implemented by GIZ and the Ministry of Trade and Industry, has successfully created Local Industrial Zones with enhanced electricity and business services (Pueyo, Bawakyillenuo, et al., 2020). However, uptake has skewed heavily toward male-owned firms, reflecting persistent gender imbalances in energy access projects. In contrast, Business Advisory Centres (BACs), local government-run hubs, have demonstrated greater gender responsiveness. These centres offer targeted support in awareness campaigns, access to finance, and training in sectors in which women are predominantly engaged, yet scale and reach remain limited. Clean cooking initiatives, including LPG expansion and behaviour change campaigns, have seen stronger engagement from women, reinforcing the importance of sectoral alignment in designing inclusive interventions.

On the financial front, women entrepreneurs in Ghana show relatively high financial inclusion, with access to bank accounts, saving mechanisms, and the ability to reinvest profits, often within the context of programmes like PSED (Pueyo, Bawakyillenuo, et al., 2020). However, these gains are not matched by access to targeted financial products for energy technologies (Schiffer & Yesutanbul, 2021). The absence of gender-sensitive finance options, such as loans for solar home systems or efficient cookstoves, restricts women's ability to expand energy access for productive use and limits their entrepreneurial potential.

Business model and financing strategy

Drawing from the scenario analysis and enabling environment review, the recommended business model for the NGO reflects a community-anchored, service-based configuration grounded in cooperative or hybrid ownership. The enterprise already provides essential processing services, including drying and intermediate cold storage as part of the fish smoking workflow. However, there is potential to expand this offering into standalone value-added services that meet the broader needs of its female clientele, primarily small-scale fish processors engaged in household consumption or market sales. This could include larger-scale cold storage available for rent, or collective product aggregation and distribution services to facilitate improved market access. These enhancements would allow the NGO to diversify revenue streams and support broader enterprise resilience within the community.

From a financing perspective, a blended capital structure is best suited to the NGO's needs, recognising its limited access to commercial finance. Concessional and public financing instruments remain central to this configuration. Programmes such as GEDAP, GPRBA, SREP, and REACT serve as important precedents, demonstrating early efforts to integrate financing, results-based models, and inclusive access within Ghana's energy sector. They demonstrate how public and donor-backed support can be mobilised to subsidise infrastructure investment. In this case, targeted subsidies, either in full or partial form, would be particularly critical for high-CAPEX components such as the greenhouse dryer and solar PV arrays needed in every enhancement scenario, the FAO-FTT kiln required in scenario 3 or the battery storage systems in scenarios 2 and 3. Subsidy support may take the form of direct infrastructure grants, equipment vouchers, or results-based disbursements, depending on the funding instrument applied. Complementary financing mechanisms, including microfinance or lease-to-own schemes from local banks, could support the acquisition of productive use appliances or balance the remaining capital requirements when subsidies do not cover total costs. These mechanisms are especially relevant for enabling user-side investments in appliances and secondary infrastructure. However, their uptake hinges on improved loan conditions, including reduced interest rates, longer tenures, and accessible collateral standards.

Regulatory and institutional constraints continue to hinder the full realisation of decentralised renewable energy models, an essential element across all proposed scenarios. A key barrier lies in Ghana's current regulatory framework, which

mandates public ownership of mini-grids (GOGLA, 2021a). This requirement not only restricts the range of viable ownership structures but also limits the operational autonomy of NGOs and social enterprises that could otherwise lead or co-manage decentralised systems. In practice, this constrains the scalability and flexibility of innovative delivery models that rely on community engagement, cost-sharing, or demand-responsive governance. While public-private partnerships or cooperative-led approaches could serve as alternatives, their legal status remains ambiguous and poorly codified, creating uncertainty for investors and implementers alike.

Risk-sharing mechanisms are equally critical and currently underutilised. Foreign exchange volatility, repayment risk, and uncertain demand profiles are core challenges for financing productive use infrastructure at the community level (GOGLA, 2021a). Mechanisms such as partial credit guarantees, RBF, or donor-backed de-risking instruments could help mitigate these risks and enhance capital flows, particularly from commercial or impact-aligned investors. Complementary ecosystem support, such as capacity building, gender-responsive business services, and local technical assistance, would also be essential to build bankability and operational viability over time.

Taken together, this business model offers a flexible, scalable, and socially embedded pathway for delivering decentralised energy services that can adapt and mature over time. Its core strength lies in integrating clean, reliable energy access with productive use services tailored to the operational realities of the implementing NGO and its end users, predominantly low-income women, including market-based entrepreneurs. Crucially, the model is structurally aligned with Ghana's national priorities around decentralised energy deployment and gender-inclusive development. In parallel, this case underscores the need for context-sensitive models that go beyond technological provision to bridge energy delivery with financing mechanisms and livelihood support. Yet, despite its promise, the enabling environment remains fragmented. Policy commitments to decentralisation and inclusion are ambitious but unevenly enforced, and financial systems remain poorly calibrated to the capital requirements of small-scale productive users. Bridging the affordability gap, particularly for clean fuels like LPG, and clarifying institutional roles will be essential to unlock scale and replication. Without these enabling reforms, such models risk remaining pilots rather than pathways for inclusive, market-driven rural energy transitions.

8.3.3.2 Case study 2: Irrigation and agri-processing in Tunisia

Case study 2 represents an enterprise owned by a sole female operating in the agricultural sector under ISIC Division 1 (Crop and animal production). This case study from Tunisia reflects the increasingly urgent need to decarbonise irrigation systems while improving agri-processing efficiency. It also highlights the potential of decentralised energy technologies to enhance productivity and resilience within Tunisia's small-scale farming sector. The findings provide an illustrative basis for further refinement through applied research, stakeholder co-development, and pilot adaptation, particularly as this case blends characteristics of both productive farming and small industrial processing.

Scenario context and energy access performance

Case study 2 encompasses irrigated farming and small-scale olive oil processing, both of which rely heavily on electricity to power borehole pumps and agri-processing equipment. Historically dependent on diesel generation and grid electricity, the enterprise has already invested in a standalone solar PV system, laying the groundwork for a transition to cleaner and more cost-effective energy services. Three enhancement scenarios were analysed, each progressively building on this base system.

Scenario 1 optimises the existing energy setup by eliminating diesel use and integrating the existing solar PV with the grid. The system powers irrigation and pumping activities, achieving a one-tier increase in MTF energy access (to tier 3) with no reliability or availability constraints. Scenario 2 anticipates modest business expansion, including a more powerful irrigation pump, while maintaining the technical configuration of scenario 1. Both scenarios report identical CAPEX (USD 28,000) and avoid fossil fuel reliance, though OPEX increases by almost 60% in scenario 2 due to greater water demand (7,000 USD/year). Scenario 3 presents a transformative model, enabling full energy autonomy through an upgraded solar PV system, battery storage, and on-site olive oil extraction. It achieves the highest final MTF tier (tier 5), full independence from the grid, and avoids 21 $tCO_{2\text{-}eq}$/year, more than any other scenario. However, it requires significant investment (USD 180,000-217,000) and carries higher OPEX (USD 11,000-13,000/year). Importantly, all scenarios yield consistent reliability, making energy performance an enabler rather than a constraint to productivity. These figures reflect the scale-dependent trade-offs between autonomy, sustainability, and affordability.

Tunisia's broader investment and regulatory context provides a mixed enabling landscape. The country ranks 78th in the World Bank's 2020 Ease of Doing Business Index, with a score of 68.7, reflecting a moderate level of procedural efficiency and market accessibility (The World Bank Group, 2020). However, Tunisia is not covered in the 2024 Business Ready assessment or the 2022 ERI, limiting the availability of updated benchmarks for regulatory governance, implementation quality, and sector performance (AfDB Group, 2022; The World Bank Group, 2024a). With respect to gender, Tunisia ranks 115th out of 146 countries in the 2024 Global Gender Gap Index, with a score of 0.668 (World Economic Forum (WEF), 2024). This indicates minor progress, pointing to persisting challenges in achieving equitable economic participation and leadership opportunities for women. These composite indicators, while not definitive, highlight areas where institutional support, regulatory clarity, and gender mainstreaming could be further strengthened to improve the enabling conditions for inclusive, small-scale renewable energy solutions, particularly those targeting women-owned agricultural enterprises.

Enabling environment: Policy, institutional and financial dimensions

Tunisia's national energy landscape presents both opportunities and constraints for decentralised energy investment in small-scale agri-processing. Electrification rates are near universal, achieved largely through grid rollout financed by public institutions and AfDB support (Hamedi et al., 2021; IRENA, 2024). Grid connection subsidies and low electricity tariffs remain in place, but they exert growing fiscal pressure on STEG, the state-owned utility (Calì & Zitouna, 2023; Hamedi et al., 2021). This has implications for long-term sustainability and capacity to accommodate distributed generation.

Tunisia's regulatory framework for renewable energy is well-developed in legal terms. Key milestones include Decree 2009/362, the Renewable Energy Law No. 74/2013, and subsequent amendments that formalised self-consumption and independent power production (Hamedi et al., 2021; IRENA, 2024). However, the lack of an independent regulatory authority and slow enforcement of reforms limit the predictability needed for private investment (Hamedi et al., 2021). Although net metering and self-generation are legally permitted, the economic terms remain suboptimal for MSMEs and rural users. Programmes such as PROSOL-Elec target households and micro-systems (Agence National pour la Maitrise de l'Energie (ANME), 2023b, 2023a; World Resources Institute, 2011), while larger-scale incentives cater to independent power producers operating under the Tunisian Solar

Plan (TSP) (Hamedi et al., 2021). Yet, the mid-scale segment, representing productive rural businesses like the present case, remains underserved.

On the financing side, Tunisia's central public vehicle is the Energy Transition Fund (FTE), created in 2013 to support renewable energy and energy efficiency (Hamedi et al., 2021). It provides grants and subsidised loans covering up to 50% of eligible investment costs, with co-financing required from commercial banks. While the fund's legal scope includes repayable advances and equity, these mechanisms remain underutilised. Critically, the FTE's operationalisation has focused on high-visibility or utility-scale projects, with limited support to decentralised agriculture-linked use cases. The Tunisian Investment Fund, though primarily focused on large-scale infrastructure, offers grants of 15-30% of investment costs under specific criteria and could be explored in future programme iterations. Similarly, capacity-building initiatives such as the National Centre for Continuous Vocational Training provide training funds for renewable energy professionals, an asset in building the skills base needed to scale operations in decentralised renewable energy access projects.

Gender-specific financing and institutional support mechanisms in Tunisia remain underdeveloped, despite increasing rhetorical and strategic attention to women's role in the energy transition. Tunisia's energy policy discourse now frequently affirms gender equity as a pillar of inclusive innovation, and national strategies such as the Green Hydrogen Roadmap (2035) explicitly include gender mainstreaming objectives (Green H2 Tunisia et al., 2024). Yet, operational translation of these goals remains limited, particularly within decentralised energy and productive use contexts. The launch of the Tunisian Women Network for Energy Transition (TWNET) in 2025, a professional network for women in energy, represents a step toward enhancing visibility and leadership, though the network's reach and institutional leverage are still evolving (Trovit, 2025).

At the programme level, regional initiatives offer a more targeted entry point. The Women on the Green Path initiative (2024-2025), supported by GIZ and the Spanish Agency for International Development Cooperation (AECID) and implemented by the Centre of Arab Women for Training and Research (CAWTAR), targets women entrepreneurs in Tunisia's green economy, providing training, mentorship, and facilitated access to renewable energy and circular economy markets (EDAMA, 2022). Similarly, REGEND, led by United Nations Economic and Social Commission for Western Asia (ESCWA) and funded by the Swedish International Development Cooperation Agency (SIDA), has piloted

productive use interventions that combine technical training in solar drying and irrigation with entrepreneurship development, illustrating how small-scale decentralised energy can be directly linked to rural women's income generation (United Nations Economic and Social Commission for Western Asia (ESCWA), 2022, 2023). These programmes could be leveraged to strengthen ecosystem readiness for scaling women-owned productive energy enterprises.

However, structural financing gaps persist. Microfinance institutions such as ENDA Tamweel reach a large proportion of women clients, approximately 70%, but typical loan sizes remain below 1,000 USD, insufficient to support medium- or high-CAPEX renewable energy upgrades and investments (ENDA tamweel, 2020; IFC, 2025). While such instruments enable access to basic appliances (e.g., solar lanterns, fridges, sewing machines), they fall short of facilitating ownership of integrated systems like solar pumping or agri-processing equipment. Moreover, conventional bank financing remains largely inaccessible to women-led enterprises due to strict collateral requirements, often approaching 100% (Women Entrepreneurs Finance Initiative (we-fi), n.d.). The absence of gender-sensitive, scale-appropriate financial products, particularly for mid-sized enterprises and rural women-led businesses, creates a critical bottleneck. Without de-risking instruments, longer loan tenures, or concessional blended mechanisms, women's participation in productive energy markets will remain limited. Donor-backed and state-supported efforts to close this financing gap are urgently needed to operationalise gender equity as more than a policy aspiration.

Business model and financing strategy

The most viable model for this enterprise is a decentralised, entrepreneur-led model that integrates core productive use with embedded energy services. Given the spatial characteristics of agricultural land and the absence of proximate off-takers, collective mini-grid or bundled consumption models are not technically or economically feasible. Instead, the enterprise itself anchors the energy infrastructure, with the potential to scale the existing productive services (irrigation, monetising surplus ground water extracted, and olive oil processing), and to add value-added services, such as cold storage, olive oil aggregation or packaging for market access. Underpinning this configuration is an electrification seed logic: by anchoring the system in a productive rural enterprise with demonstrated demand, the model facilitates bottom-up expansion and eventual bundling of services. This approach aligns with Tunisia's self-consumption legal framework and can evolve

through modular investment stages. However, for this pathway to mature, financial de-risking and institutional reforms are essential.

From a financial standpoint, the case clearly demands a blended capital structure. Public and concessional funds remain central to enabling the high upfront investment, particularly under scenario 3, which includes a new solar PV system, battery storage, and a small industrial olive oil press. Targeted grant components, such as those from the FTE, could support the infrastructure build, especially if aligned with Tunisia's Nationally Determined Contributions and broader low-carbon development commitments (Hamedi et al., 2021). However, FTE-backed loans require parallel co-financing from local banks, a constraint that is difficult to overcome without the mobilisation of risk-sharing tools. Institutions such as the Tunisian Guarantee Company, AFD, or the International Finance Corporation (IFC) could play catalytic roles in this space by offering credit enhancements and de-risking instruments that enable greater participation from domestic financial actors.

Previous experiences in the renewable energy sector offer important precedents but highlight mismatches with the current case. The Prosol-Elec scheme, for instance, successfully enabled household-scale PV adoption through a blended utility billing mechanism, but its design does not extend to commercial agricultural enterprises (ANME, 2023a, 2023b; World Resources Institute, 2011). Similarly, Tunisia's regulatory framework under the Tunisian Solar Plan does allow for self-generation and independent power production for consumption (Hamedi et al., 2021), but the associated tariffs and transaction costs remain better suited to large-scale producers than MSMEs (STEG, 2023). A new mechanism, such as the solar water pumping finance approach proposed in national policy recommendations (Hamedi et al., 2021), could be adapted to serve enterprises like this one, where seasonal irrigation and agri-processing operations require reliable and affordable power without grid dependence. Institutionally, the entrepreneur presents a credible anchor. Having already accessed and successfully implemented both a national subsidy and a donor-backed grant from the ProAgro Foundation, the enterprise demonstrates an established capacity to engage with public and donor financing instruments. This record strengthens the business case for future applications, especially under programmes seeking demonstrated field-level impact. It also underscores the importance of decentralised, accessible financing windows that can be absorbed by local women entrepreneurs, reinforcing the case for tailored public-private schemes that offer both upfront grants and technical support.

Complementary financial mechanisms could also play a supporting role. Lease-to-own models might be appropriate for modular equipment such as battery storage, especially if concessional terms can be secured to reduce affordability barriers. Microfinance providers such as ENDA Tamweel have experience reaching women entrepreneurs in rural contexts, but loan ceilings (typically below 1,000 USD) remain insufficient for scaling energy assets (ENDA tamweel, 2020; IFC, 2025). Expanding these ceilings and embedding energy-focused, gender-responsive loan products, potentially backed by blended finance or international guarantees, could help fill this financing gap.

Beyond capital, vocational training and technical assistance emerge as critical enablers for long-term viability. The enterprise would benefit from targeted capacity-building on energy system optimisation, post-harvest processing, and agri-market development. Tunisia's national vocational training ecosystem, funded by earmarked tax revenues and managed by specialised training centres, offers a structurally sound platform for delivering such support (Hamedi et al., 2021). These public resources could be leveraged to align technical training with the energy and agri-processing sectors. Simultaneously, regional programmes like Women on the Green Path (2024–2025), which provide mentorship and green sector market access to women entrepreneurs, offer entry points for strengthening the broader ecosystem (EDAMA, 2022). Integrating energy access improvements with skill development and market linkages would enhance enterprise resilience and create spillover benefits for the wider rural economy.

Taken together, this case study exemplifies a grounded and adaptable model for enhancing productive use through decentralised energy systems in rural Tunisia. Anchored in entrepreneurial initiative and supported by a progressively structured yet underutilised policy landscape, the model integrates reliable clean energy with value-added agricultural services, framed by a business strategy that reflects real enterprise needs. Its viability, however, extends beyond technical performance; it relies on a synergistic enabling ecosystem where tailored financing, policy coherence, and institutional coordination align to support implementation and scale. To move from isolated success to broader transformation, future efforts must prioritise legal clarity, institutional coordination, and sustained investment in both people and infrastructure. Only through such an integrated and inclusive approach can Tunisia's energy transition meaningfully engage and empower its rural enterprise base.

8.3.3.3 Case study 3: Dairy production and cereal milling in Kenya

Case study 3 represents a jointly owned dairy and cereal processing enterprise in Kenya, situated within ISIC Division 10 (Manufacture of food products). The analysis explores a transition from grid electricity and diesel reliance to clean and decentralised energy solutions across four distinct scenarios. Each scenario models technological shifts in electricity and thermal energy systems and quantifies implications for investment costs, GHG emissions, and enterprise-level performance. By linking these findings to Kenya's broader policy and financing ecosystem, the case contributes to identifying scalable approaches for productive use in the dairy and agri-processing sector, with particular emphasis on gender responsiveness and energy-market integration.

Scenario context and energy access performance

This case study explores the energy transition pathway of a dairy and cereal milling enterprise located in rural Kenya, jointly managed by a husband and wife. The business processes locally sourced milk and grains and serves surrounding communities. The assessment considers four renewable energy upgrade scenarios designed to improve environmental performance, energy reliability, and economic viability.

Scenario 1 introduces a modest intervention by installing solar PV with net metering at the cereal milling facility, while the dairy plant maintains its base case setup, drawing electricity from the grid, using diesel backup during outages, and continuing with the biomass briquette boiler for thermal needs. As such, this scenario achieves modest GHG mitigation (60 $tCO_{2\text{-}eq}$/year), reaches MTF tier 3, and retains vulnerability to power disruptions. Scenario 2 builds on this by introducing battery storage, achieving complete electrical autonomy for both the dairy and cereal milling operations. The dairy plant's cooling and electrical systems are powered entirely by solar PV and batteries, while thermal demand at the dairy plant continues to be met by the existing briquette boiler. Scenario 2 preserves the same thermal setup as scenario 1 but eliminates grid and diesel reliance. It maintains a final MTF tier of 3 and significantly boosts environmental performance with GHG emissions avoided of 134 $tCO_{2\text{-}eq}$/year. Investment costs range between 3-4 million USD. Scenario 3 further transforms the energy system by fully electrifying the dairy plant's thermal needs through the integration of a high-temperature heat pump. This transition necessitates a substantial increase in solar PV and battery capacity, driving total investment to approximately 5.6 million USD. The cereal milling

facility retains its autonomous electrical configuration from scenario 2. With a final MTF tier of 5 and the same emissions reduction as scenario 2 (134 $tCO_{2\text{-}eq}$/year), scenario 3 exemplifies full decarbonisation through electrification. Scenario 4 offers an alternative thermal solution by deploying an AD system to produce biogas for a new boiler at the dairy plant. This option sustains full autonomy and MTF tier 5, like scenario 3, while maintaining identical emissions performance (134 $tCO_{2\text{-}eq}$/year). It does so at a lower capital cost, approximately 3.5 million USD and achieved the lowest operational costs between 47,000 and 146,000 USD/year compared to the other enhancement scenarios. Across scenarios 2 through 4, full energy availability is assumed with no reliability issues. The cereal milling component, requiring electricity only, is treated consistently in all scenarios and transitions from partial to full autonomy beginning in scenario 2. Together, these scenarios demonstrate the flexibility of combining technical configurations to enhance sustainability and resilience in integrated agri-processing enterprises.

Kenya's broader investment climate and policy frameworks offer a relatively robust, though still evolving, foundation for decentralised energy transitions. Ranking 56th globally in the 2020 Ease of Doing Business Index (score: 73.2), Kenya demonstrates moderate ease in navigating market entry and regulatory procedures, a critical factor for financiers and private sector actors involved in energy access projects (The World Bank Group, 2020). Its performance in the 2022 ERI is classified as substantial, indicating an established institutional structure capable of supporting energy sector reform and innovation (AfDB Group, 2022). With respect to gender equity, Kenya ranks 75th globally in the 2024 Global Gender Gap Index (score: 0.712), underscoring steady institutional efforts to integrate gender in policy processes and growing momentum across key sectors (World Economic Forum (WEF), 2024). However, gender-differentiated challenges persist, especially in translating policy commitments into equitable access to resources and productive opportunities. Together, these indicators portray a national context that is increasingly conducive to inclusive and sustainable energy models, though further refinements in gender-responsive financing and coordinated implementation will be essential to fully enable enterprise transformation.

Enabling environment: Policy, institutional and financial dimensions

Kenya's decentralised energy transition is underpinned by a comparatively mature and forward-looking policy architecture. The 2018 National Electrification Strategy provides the strategic anchor, outlining a least-cost pathway to universal energy access that combines grid densification, extension, and off-grid modalities,

including mini-grids and standalone solar systems (Barasa et al., 2020; GOGLA, 2021b). The Energy Act of 2019 further consolidated institutional roles by establishing EPRA and the Rural Electrification and Renewable Energy Corporation (REREC), while mandating County Energy Plans to ensure alignment between national objectives and subnational implementation (Barasa et al., 2020; Ongeri & Musonye, 2024). These reforms have clarified mandates and supported decentralised planning, though implementation capacity remains uneven across counties. Kenya's power sector is structurally conducive to private participation, owing to partial unbundling (Barasa et al., 2020). KPLC remains the sole off-taker and distributor for grid electricity, while generation is divided between KenGen (public), independent power producers (IPPs), and imports. KETRACO oversees transmission, and EPRA manages tariff regulation and licensing. Instruments like the Feed-in Tariff policy (2008), later replaced by competitive auctions and net metering mechanisms, have helped attract IPPs in solar, wind, and small hydro (Barasa, 2020; Ongeri, 2024). These structural elements support private sector engagement while providing investor confidence through tariff stability and long-term power purchase agreements.

Substantial gains have been made in expanding household access through targeted subsidies. The Last Mile Connectivity Project, co-financed by the Kenyan government and international donors, significantly lowered connection fees, reducing the household contribution from around USD 1,000 to USD 150, with the Stima Loan facility enabling payment in instalments over three years (Barasa et al., 2020). Similarly, to reach urban informal settlements, Kenya implemented a Slum Electrification Project (SEP) as part of an earlier World Bank-funded energy project . The connection fee was reduced to about 15 USD payable in instalments, removing the earlier 350 USD connection fee. A study in Western Kenya showed that even heavily subsidised connections remained underutilised unless credit constraints were explicitly addressed (Innovations for Poverty Action (ipa), 2021). While these efforts succeeded in broadening access among households, small enterprises often requiring three-phase upgrades have remained underserved, facing high fees and supply unreliability that limit productive energy use.

In the off-grid domain, Kenya has positioned itself as a continental leader, driven by innovation PAYGo business models and supported by a vibrant private sector (GOGLA, 2021b). Companies like M-KOPA, d.light, and Sun King scaled rapidly with the support of the Lighting Africa programme, which helped build consumer awareness, set quality standards, and reduce import duties for solar components. Public-private partnerships have been particularly impactful under the

Kenya Off-Grid Solar Access Project (KOSAP), which blends mini-grid deployment with clean cooking and RBF. KOSAP's model, using capital subsidies and uniform tariffs to attract licensed operators, has facilitated the rollout of 151 mini-grids in underserved counties, ensuring affordability through cross-subsidisation and donor support (Barasa et al., 2020).

Complementing electrification efforts, the clean cooking agenda has advanced through initiatives led by GIZ EnDev, the Clean Cooking Alliance, and the Clean Cooking Association of Kenya (CCAK) (Barasa et al., 2020; Clean Cooking Association of Kenya (CCAK), 2025). The introduction of biogas digesters and improved biomass stoves has been catalysed by donor subsidies and technical training, although uptake in the agri-processing sector remains limited due to scale and reliability concerns (Barasa et al., 2020). The clean cooking component of KOSAP also uses RBF to incentivise stove sales and build last-mile distribution networks, with a strong emphasis on women-led sales agents in rural areas.

Financially, Kenya's landscape has reached moderate maturity, with growing experimentation in climate-linked and blended finance. Multilateral donors, such as the World Bank, AfDB, AFD, and EU, have anchored large-scale concessional funding for both grid and off-grid infrastructure, while newer instruments explore the monetisation of emissions savings (Barasa et al., 2020; GOGLA, 2021b; Sustainable Energy for All (SE4ALL), n.d.). The Africa Carbon Markets Initiative, for instance, is exploring linkages between clean energy expansion and carbon credit generation to finance solar and clean cooking adoption (SE4ALL, n.d.). Simultaneously, local innovation ecosystems are being catalysed through venture and impact funds. The Africa Enterprise Challenge Fund and KawiSafi Ventures Technical Assistance Facility (KSV TAF), backed by the Green Climate Fund, have supported energy MSMEs with firm-level support focused on gender inclusion, consumer protection, and financial readiness (GOGLA, 2021b). Mobile money platforms such as M-Pesa have further enabled PAYGo solar uptake, showcasing the synergy between financial innovation and energy access. The Kenyan government has complemented donor efforts by maintaining fiscal incentives for clean energy investments (Barasa et al., 2020; GOGLA, 2021b). Solar and wind equipment imports are exempt from duties, while energy developers benefit from long-term PPA frameworks. Public revenue streams such as the Rural Electrification Program Levy also sustain recurrent investments in rural connectivity, including power provision to schools, water systems, and low-income settlements. Future expansions may integrate these fiscal tools with results-based

modalities and carbon-linked finance, offering scalable models for mid-size enterprises currently excluded from traditional energy financing schemes.

Gender integration in Kenya's energy sector has progressed significantly over the past decade, with both national and county-level policy shifts. A gender focal point was appointed at the Ministry of Energy in 2016, followed by the launch of Kenya's first Gender Policy in Energy in 2019 (Practical Action, 2023b). These policy instruments have been reinforced by development partners and civil society through initiatives like ENERGIA and Practical Action, which have focused on fostering women energy entrepreneurs and mainstreaming gender across institutional structures. The Women in Energy Enterprises in Kenya (WEEK) programme (2022-2024) stands out, supporting over 400 women with business training, finance facilitation, and mentorship, including over 300 women energy entrepreneurs, and over 60 women involved in productive energy use, such as milling and refrigeration (Practical Action, 2024). Some counties, such as Embu, have gone further by incorporating gender-sensitive budgeting into County Energy Plans, setting aside resources to support women entrepreneurs through co-financing schemes and public exhibition spaces. Nevertheless, significant gaps remain. Most financial instruments accessible to women remain small-scale, such as clean cookstove and solar home system loans offered by institutions like Kenya Women Microfinance Bank (KWFT) (Kenya Women Microfinance Bank PLC (KWFT), 2025). For medium-scale, asset-intensive enterprises such as agri-processing ventures, accessible financing remains scarce. Bridging this gender-financing gap requires a dual approach: aligning national energy and climate finance instruments with gender-responsive mechanisms and expanding tailored credit and equity products that explicitly target women-led or co-owned productive enterprises.

In summary, Kenya's enabling environment presents a robust, albeit evolving, foundation for decentralised energy transitions. Strong policy frameworks, institutional reforms, and donor-financed programs provide critical building blocks. Yet, targeted interventions are required to extend these gains to the productive use segment, particularly for mid-scale enterprises and women-led ventures. Doing so will require calibrated reforms in subsidy targeting, financial product design, and decentralised implementation capacity, underpinned by continued gender integration at both institutional and operational levels.

Business model and financing strategy

The most viable business model for this enterprise builds on its unique structure as a co-owned agri-processing facility that is vertically integrated, meaning it is involved in multiple stages of the value chain, from sourcing local milk and grains to processing and distribution. This strong connection to local producers and its embedded role in the rural economy make it a natural anchor enterprise, capable of linking productive energy services with value-added agricultural outputs. This potential becomes especially important in scenarios 2 through 4, where renewable energy investments allow the enterprise to shift from treating energy as a basic operational cost to using it as a strategic service. In scenario 4, the addition of an AD system introduces a circular economy element: cow manure is converted into thermal energy and nutrient-rich fertiliser (digestate), which can be supplied back to farmers. This not only creates an additional revenue stream but also strengthens local supply chains. Altogether, the model demonstrates how agri-processing can be combined with decentralised energy services to support rural industrialisation in an inclusive and sustainable way.

Structurally, the enterprise is well-positioned to mobilise blended finance. Its joint ownership model, rooted in spousal entrepreneurship and community-based engagement, offers potential for pooling equity and aligning incentives across a diverse set of stakeholders. This is especially pertinent as scenarios 2 to 4 involve a CAPEX between 3-5.6 million USD, levels that far exceed the capacity of conventional microfinance or community-based savings. In this context, a layered financing structure becomes essential. Concessional capital from DFIs, such as the Green Climate Fund, the AfDB, or the World Bank, could play an anchor role, de-risking early-stage investments. This can be achieved through tools like partial credit guarantees and subordinated debt instruments, where the DFI agrees to take lower repayment priority in the event of losses. By absorbing more of the financial risk, these instruments can make the project more attractive to commercial investors and help crowd in private capital. Technical assistance facilities like the Africa Enterprise Challenge Fund and KawiSafi Ventures may also be leveraged to improve bankability and support pre-investment structuring, particularly for battery storage, solar PV, and biogas systems.

RBF mechanisms, as successfully piloted under the KOSAP, offer a particularly promising instrument to incentivise the adoption of high-impact, climate-aligned technologies. Under such schemes, grants are disbursed upon achievement of predefined outputs, such as GHG emission reductions, clean energy

service provision, or inclusive ownership metrics, thus aligning donor priorities with enterprise performance. Scenarios 2 to 4, which contribute to the decarbonisation of electrical and thermal systems, would qualify strongly under these criteria. Furthermore, scenario 4's deployment of a biogas boiler offers eligibility for future monetisation of carbon savings under frameworks like the Africa Carbon Markets Initiative. While the operationalisation of such carbon markets for MSMEs remains nascent, their integration into investment appraisals could enhance long-term returns and improve alignment with Kenya's Nationally Determined Contributions.

Mobilising private finance will hinge on targeted risk mitigation and financial innovation. While impact investors are increasingly drawn to energy access and climate-resilient agriculture, mid-scale enterprises such as this one face persistent constraints stemming from modest transaction sizes, perceived risk exposure, and limited financial documentation or formal credit history. To bridge this gap, tailored financial instruments, such as equipment leasing, cooperative lending pools, or multi-party guarantees, will be essential. Although PAYGo models are not directly transferable from the household solar context, their underlying logic can be adapted to asset-backed leasing arrangements for battery systems or AD, where capital cost recovery is staggered over time through service-based payments. Such models could even be integrated into a cooperative framework, allowing the enterprise to aggregate smaller contributions from members while retaining control over critical energy infrastructure.

Importantly, gender-responsive finance must be embedded in the business model to ensure that the joint ownership structure translates into equitable access to capital and decision-making power. While women-oriented microfinance products exist for small-scale energy access, such as cookstoves or solar lanterns, these are insufficient for the scale of investment required under the enhancement scenarios. Dedicated financing lines for women-owned productive enterprises are needed, including longer loan tenures, reduced collateral requirements, and embedded non-financial services such as mentorship and technical training. The WEEK programme, which has demonstrated success in supporting women entrepreneurs in productive use of energy, provides a replicable framework for integrating enterprise development with financial facilitation and market access. At the subnational level, gender-sensitive budgeting processes, such as those pioneered in Embu County, could be mobilised to co-finance equipment or support public-private partnerships aimed at inclusive agri-processing clusters.

Ultimately, this business model aligns technical innovation with financial inclusion and gender-responsive design. It expands the concept of productive use, positioning energy not merely as an input but as a platform for rural enterprise development that delivers economic, social, and environmental value. Its strength lies in adaptability: it can integrate both electrification and thermal energy solutions, support diverse ownership structures, and align with emerging policy instruments in Kenya's decentralised energy framework. However, scalability remains constrained by persistent financing barriers, particularly within the "missing middle", where enterprises are too large for microfinance but too small or high-risk for commercial banks and institutional investors. Bridging this gap will require targeted financial instruments and institutional mechanisms that recognise and reward co-benefits such as gender equity, climate resilience, and local economic development. In this light, the Kenya case offers a compelling example of how decentralised energy can catalyse inclusive rural industrialisation. Its long-term viability depends not only on renewable technologies but on the effective coordination of finance, policy, and enterprise support systems that can enable systemic transformation. As Kenya continues to refine its regulatory landscape, expand fiscal incentives, and embed gender equity across development planning, models like this provide a grounded, scalable pathway for climate-aligned and socially embedded energy transitions.

8.3.3.4 Case study 4: Maize milling in Malawi

Case study 4 represents an enterprise that is jointly owned by a married couple engaged in ISIC Division 10 (Manufacture of food products). It operates within a challenging energy landscape where access remains severely limited. The analysis models a transition away from exclusive diesel reliance toward renewable energy-based systems, assessing three alternative scenarios across performance, investment, and environmental dimensions. Through this lens, the case highlights Malawi's evolving energy access policy ecosystem, the financial tools available for decentralised actors, and the persistent gender and regulatory constraints shaping enterprise-level outcomes. The findings contribute to identifying feasible business models for productive use in energy-poor settings, where investment risk, affordability, and institutional maturity remain key variables.

Scenario context and energy access performance

The baseline condition for this enterprise is a total dependence on diesel-powered generators to operate its maize milling activities. This energy setup is

costly, emissions-intensive, and vulnerable to fuel price volatility, which constrains operational viability and productivity. To address this, three transition scenarios were modelled, each offering different pathways to reduce carbon intensity and improve cost efficiency while maintaining operational continuity.

Scenario 1 adopts a hybrid configuration combining diesel generators with solar PV. This setup retains the diesel system but supplements it with renewable generation, reducing fuel consumption and offering moderate environmental benefits (32 $tCO_{2\text{-eq}}$ avoided/year). With a capital cost of 35,000 USD and operating expenses of USD 8,000/year, this entry-level solution provides a minor cost improvement without eliminating fossil fuel dependency. It achieves MTF tier 3 and ensures operational reliability but remains fully reliant on diesel during periods of low solar availability. Scenario 2 replaces diesel generators entirely with standalone solar PV systems supported by battery storage and achieves full autonomy and MTF tier 5, while eliminating GHG emissions (48 $tCO_{2\text{-eq}}$ avoided/year). Notably, with an initial investment between 32,000-51,000 USD, scenario 2 delivers a transformative shift in annual operating costs, accounting for 3,000 USD/year. Scenario 3 offers a distinct decarbonisation pathway through the retrofitting of existing diesel engines for dual-fuel operation with syngas produced by an on-site biomass gasifier. This system reduces diesel consumption, maintains MTF tier 5 access, and avoids 36 $tCO_{2\text{-eq}}$/year. However, it carries the highest CAPEX (USD 259,000) and annual operating costs of 23,000 USD/year, primarily due to the additional infrastructure and complexity of gasifier operation. While the hybrid fuel model allows continued use of existing assets, the scenario demands higher technical capacity and introduces operational risks, making it best suited for enterprises with robust management and access to advanced support systems.

From a broader investment and regulatory standpoint, Malawi presents a mixed enabling environment for decentralised energy transitions. Ranked 109th globally in the 2020 Ease of Doing Business Index (score: 60.9), the country exhibits considerable procedural barriers to enterprise formalisation and infrastructure investment (The World Bank Group, 2020). Meanwhile, its ERI classification remains at a “low” level, reflecting limited institutional capacity for regulating modern electricity services and insufficient policy responsiveness to decentralised energy needs (AfDB Group, 2022). Neither the World Bank’s 2024 Business Ready indicators nor the Global Gender Gap Index (2024) provide disaggregated data for Malawi, constraining comparative analysis (The World Bank Group, 2024a; World Economic Forum (WEF), 2024). Nonetheless, anecdotal evidence and national policy frameworks suggest an increased willingness to integrate gender and

decentralised energy access into national strategies. This case therefore offers a relevant reference point for navigating low-capacity regulatory environments while pursuing energy autonomy through technically viable, capital-efficient configurations.

Enabling environment: Policy, institutional and financial dimensions

Malawi's policy framework for energy access has evolved substantially in recent years, providing an increasingly structured, albeit capacity-constrained, foundation for decentralised electrification. The Malawi Renewable Energy Strategy 2017 lays out concrete targets for on-grid renewables, off-grid solar and mini-grids, and sustainable bioenergy (Jagger et al., 2022; Latif et al., 2025). Since 2017, IPPs have been able to supply the grid, and generation assets were formally unbundled with the creation of EGENCO. The Electricity Supply Corporation of Malawi Limited (ESCOM) now serves as the transmission-distribution monopoly and sole off-taker under a single-buyer model. MERA oversees licensing, tariffs, and service quality, and regulates mini-grids. This policy direction is complemented by the National Energy Policy 2018, which establishes universal access as a core objective, underpinned by commitments to private sector participation, renewable energy diversification, and social inclusion. However, regulatory responsiveness remains weak, particularly in addressing the distinct needs of off-grid operators, cooperative utilities, and community energy providers.

Grid expansion has traditionally been driven by the Malawi Rural Electrification Programme (MAREP), now in its ninth phase, co-financed through the Africa Development Fund and donor partners (Jagger et al., 2022). While MAREP has delivered important infrastructure gains, the pace of expansion remains slow, and rural electrification stands below 5% (GOGLA, 2021c; Government of Malawi, 2018; Jagger et al., 2022). The programme is supported by a levy-funded Rural Electrification Fund and governed through the Rural Electrification Management Committee (REMAC), but challenges in procurement, utility capacity, and technical design continue to constrain outcomes. To address affordability barriers, Malawi maintains a lifeline tariff to support low-income users, and the Ndawala Initiative was introduced to provide soft loans for internal wiring, repaid via automatic deductions from prepaid meter credits (Ministry of Energy, 2020b). This demand-side subsidy mechanism has helped address one of the critical non-tariff barriers to electrification: the high upfront cost of household wiring.

For decentralised energy solutions, the enabling environment is growing in depth. The Malawi Electricity Access Project (MEAP, 2020-2025) plays a central role, with 150 million USD in World Bank financing to support both grid and off-grid expansion (Ministry of Energy, 2020a). MEAP's off-grid component channels 30% of its funds through RBF grants, complemented by a dedicated debt facility representing 70% of the off-grid envelope (Jagger et al., 2022). This structure enables private solar companies to access working capital and scale operations in underserved areas. Local enterprises such as Zuwa Energy, Green Impact Technologies, and Vitalite Group have expanded their footprint under this scheme (Ministry of Energy, 2020a). In addition, the Ngwee Ngwee Ngwee Fund, launched under MEAP, blends public and private capital to offer both loans and RBF subsidies, incentivising rural market penetration. These instruments represent promising models for de-risking private engagement in remote energy markets, though their scalability and administrative efficiency remain areas for monitoring.

Complementary efforts are visible in the clean cooking and productive use domains. Malawi's National Charcoal Strategy (2017-2027) targets improved cookstoves, sustainable biomass, and fuel-switching to LPG and biogas (Republic of Malawi & Ministry of Natural Resources, 2017). However, clean cooking uptake remains low due to affordability constraints and weak supply chains (Jagger et al., 2022; Republic of Malawi & Ministry of Natural Resources, 2017). Despite multiple donor-led pilots, the infrastructure and consumer finance necessary for large-scale adoption are still underdeveloped, especially for energy-intensive sectors like agri-processing. The Access to Clean and Renewable Energy (ACRE) Project (2020-2023), led by the Ministry of Energy and UNDP, stands out as a model for integrated energy and enterprise support (Ministry of Energy, 2020a; UNDP, 2024). ACRE's focus on mini-grids linked to productive energy hubs and rural cooperatives, targeting 50% women representation, offers a gender-responsive entry point for energy-service integration. Through procurement support, institutional training, and feasibility studies, ACRE is actively building local capacity, though long-term financing channels for productive use investments remain nascent.

Malawi's financing ecosystem for decentralised energy is shaped by strong donor involvement, modest private sector depth, and emerging experimentation with blended finance. Aside from MEAP, grant-funded programmes such as the EASE Project, UNDP's ACRE, and EnDev Malawi have enabled infrastructure roll-out, technical assistance, and policy development (GOGLA, 2021c). The Africa Clean Energy Technical Assistance Facility (ACE-TAF), supported by the

UK's FCDO, has worked to crowd in private capital through support for enterprise diagnostics and business model innovation. Yet access to commercial lending remains highly restricted, particularly for medium-scale productive use enterprises. NGOs and civil society-led investment mobilisation, such as United Purpose, Community Energy Malawi, MMCT, Renew'N'Able, and Maeve Project, work to attract funding, implement renewable energy projects, and enhance household energy access through community-focused delivery (Jagger et al., 2022). These actors often bridge financing gaps for last-mile communities by blending donor funds with local capacity building and small-scale system deployment, but predominantly remain limited in scale and sectoral reach.

Gender considerations are increasingly embedded within Malawi's energy policy and programme landscape. The 2018 National Energy Policy identifies social and gender inclusion as a cross-cutting priority, and coordination between the Ministries of Energy and Gender has notably improved (Government of Malawi, 2018; Ministry of Energy, 2020b). One outcome of this coordination is the Ndawala Initiative, under which the Ministry of Gender helped identify ultra-poor, often female-headed households to receive subsidised solar home systems (Ministry of Energy, 2020b).

At the programme level, several initiatives now explicitly target women as both energy users and entrepreneurs. Under the "Powering Gender Equality" component of UNDP's Access to Clean and Renewable Energy (ACRE) project, women were prioritised as early beneficiaries of new mini-grid connections (Ministry of Energy, 2020a; UNDP, 2024). Paired with targeted training, this access enabled women to launch and grow small businesses, demonstrating how community-based electrification can unlock economic empowerment when coupled with capacity support. Similarly, SolarAid's "Mayi Walas" (Shining Mothers) initiative equips rural women to run solar micro-businesses by distributing solar lamps and phone chargers in off-grid communities (SolarAid, 2025). The programme leverages Village Savings and Loans (VSL) groups to identify credible entrepreneurs, provides start-up credit, and enables long-term business scaling through FEBCO, a dedicated microfinance institution.

Despite this growing momentum, productive use energy investments remain largely gender-blind, particularly for women-led agri-processing ventures (Practical Action, 2023a). Access to tailored credit, enterprise development services, and energy-integrated equipment is still limited. A notable exception is the Renewable Energy for Agriculture (RE4A) project (2021-2023), implemented

by Practical Action and MFT with support from GIZ and the Powering Renewable Energy Opportunities (PREO) Fund. The initiative supported 135 women farmers through a contract farming model that bundled greenhouses, solar irrigation pumps, and solar-powered refrigeration with rent-to-own financing. Women repaid 25% of their sales toward asset ownership, thereby building informal credit histories. The model also offered agricultural training, business support, and guaranteed market linkages, significantly increasing productivity and income security.

Gender considerations are now embedded within Malawi's energy policy framework. The 2018 National Energy Policy identifies social and gender inclusion as a cross-cutting priority, and coordination between the Ministry of Gender and Ministry of Energy has improved. For example, under the Ndawala Initiative, the Ministry of Gender helped identify ultra-poor, often female-headed households to receive subsidised solar systems (Ministry of Energy, 2020a). At the programme level, initiatives such as SolarAid's Mayi Walas and UNDP's ACRE explicitly target women as distributors, beneficiaries, and co-owners of decentralised energy assets (SolarAid, 2025; UNDP, 2024). Nonetheless, energy-sector investments at the productive use level remain largely gender-blind, with limited access to tailored credit, training, or enterprise development support for women-led processing ventures. The Renewable Energy for Agriculture (RE4A) project offers a notable exception, bundling irrigation, refrigeration, and greenhouse technologies with rent-to-own financing and guaranteed market access for women farmers (Practical Action, 2023a). These innovations illustrate the potential of integrated, inclusive finance models, though their application to energy-intensive agri-processing enterprises is still emerging.

In summary, Malawi's policy and institutional landscape presents a complex mix of ambition, donor dependence, and implementation constraints. While major building blocks for decentralised energy and gender mainstreaming are in place, the depth and coordination of delivery mechanisms, particularly for productive users, remain limited. Advancing scalable and inclusive energy transitions will require deeper regulatory reform, stronger capital market engagement, and the design of gender-responsive financial products capable of supporting medium-scale enterprises beyond household-level access. For instance, emerging models, combining decentralised energy access, inclusive financing, and embedded enterprise support, offer strong evidence of what could work. They demonstrate that when energy is aligned with women's productive roles and backed by financial and institutional support, the result is not only improved livelihoods but also enhanced rural resilience and gender equity. However, most interventions remain pilot-scale,

and integrated support for medium-scale, energy-intensive enterprises, especially those led by women, is still nascent. Only through integrative efforts can Malawi move from isolated success stories to a coherent, inclusive, and sustainable energy transition.

Business model and financing strategy

The decentralised energy transition model explored in this maize milling case is anchored in a hybrid entrepreneurial-community context, where the enterprise functions as both the primary productive load and a potential service hub for an off-grid rural village. Jointly owned by a married couple, the business processes maize for most of the surrounding households, making it not only economically essential but also deeply embedded in the local socio-economic fabric. In the absence of an anticipated grid extension, this role positions the enterprise as a credible anchor for broader energy service delivery.

Scenario 1, despite its modest emissions reduction and continued reliance on fossil fuels, presents a practical and widely adopted transitional model for rural productive use enterprises. The hybrid solar PV-diesel configuration leverages the familiarity and reliability of diesel systems while introducing renewable generation during daylight hours, thus reducing fuel consumption and lowering operating costs. Technologically, this model builds directly on the existing diesel setup, requiring minimal behavioural or operational shifts, which can be a critical factor for rural enterprises. From a business model perspective, this scenario aligns with a straightforward entrepreneur-led delivery model, where investment is internalised or co-financed through microenterprise development schemes. Given the upfront cost of around USD 35,000, this model is financially relatively accessible and can be supported through a mix of local and external financing. Community-based savings groups or cooperative funds could help cover part of the investment, while the remaining amount could be sourced from donor-backed grants or small enterprise support schemes. Subsidies or RBF offered under programmes like MEAP or EnDev Malawi could reduce the effective cost of the solar PV system by reimbursing part of the installation cost once the system is operational (GOGLA, 2021c; Ministry of Energy, 2020a). To support day-to-day expenses such as fuel, repairs, or spare parts, the enterprise could also access working capital loans or use revolving funds set up by local development programmes. This layered financing approach makes the model viable for small rural businesses seeking to reduce diesel costs without taking on complex or high-risk investments. However, its limited

transformative potential underscores the need to position it as a stepping stone toward more advanced, resilient, and climate-aligned configurations.

Scenario 2 offers the strongest foundation for a viable and scalable business model. By achieving full autonomy through solar PV and battery storage, this configuration not only eliminates fossil fuel dependency but also generates surplus electricity beyond the enterprise's milling needs. This surplus, already embedded in the system design and potentially further increased through modest oversizing, creates an opportunity to extend basic household-tier electricity access to nearby residents for lighting, phone charging, and other services. Any such expansion would require separate technical assessments to define load profiles, system protection, and regulatory compliance, but the configuration aligns closely with Malawi's evolving policy emphasis on integrated productive and residential energy services. The potential to extend energy services to households introduces new considerations around system governance and financial structuring. A shared-use model, whereby the privately owned solar-PV-powered mills continue to operate the system while surplus electricity is allocated to nearby homes, could be negotiated through structured service agreements. If community savings groups or local development committees contribute to capital costs, this could justify limited co-ownership or oversight rights, without displacing the enterprise's primary ownership or operational control. Tariff design would be central to this model: rates must balance affordability for low-income households with sufficient cost recovery to maintain system integrity. Alignment with mini-grid tariff regulations under MERA and engagement with local leadership structures would be crucial to ensure legitimacy and sustainability. These dynamics mirror recent programme innovations in Malawi, such as the UNDP-led ACRE initiative, reinforcing the potential of this maize mill to serve as an anchor for integrated energy services, provided technical assistance and community buy-in are ensured from the project initiative (Ministry of Energy, 2020a; UNDP, 2024). While the maize milling enterprise operates at a different scale, lessons from SolarAid's "Shining Mothers" initiative remain relevant. The underlying principles are similar: training should be modular, practical, and tailored to match the literacy levels and time constraints of enterprise owners, ensuring accessibility and effectiveness (SolarAid, 2025). Capacity building could further be linked to local cooperatives or microfinance institutions, as done through FEBCO in the "Shining Mothers" programme, to ensure continuity and reinforce financial discipline. Capacity building could be further supported by industry associations, development partners, energy cooperatives, or national programmes such as the Renewable Energy Industries Association of Malawi (REIAMA), ACRE or MEAP, out of which some have

previously demonstrated success in institutional support and technical training in comparable settings (Jagger et al., 2022). However, such models must be approached with care to avoid over-burdening the entrepreneurs. Scenario 2's economic profile reinforces its viability: with capital costs between USD 32,000-51,000 and minimal operating expenses (USD 3,000/year), the system represents a cost-effective and environmentally sound investment. Its alignment with Malawi's MEAP framework is particularly advantageous. The programme offers concessional debt and RBF through its off-grid component, while the Ngwee Ngwee Ngwee Fund enables additional layering of grant and loan instruments for systems targeting last-mile users (Ministry of Energy, 2020a). Loan repayment could be structured around the enterprise's stable milling revenues, potentially augmented by service fees from residential users.

Scenario 3, while more complex and capital-intensive (USD 259,000), introduces an alternative model that links energy production to local agricultural systems. By retrofitting the diesel generator for dual-fuel operation using syngas from a biomass gasifier, this scenario offers dual benefits: reduced diesel reliance and production of biochar, a nutrient-rich by-product that could serve as an organic fertiliser for local farmers. Moreover, integrated productive energy models such as those demonstrated under the RE4A project (Practical Action, 2023a), where rent-to-own schemes were bundled with agricultural support and guaranteed market linkages, offer a viable template for expanding the value proposition of scenario 3. If biochar from the gasifier can be reliably produced and distributed, a similar bundling mechanism could be used to offer a fertiliser to local farmers while amortising energy costs through in-kind contributions or crop contracts, particularly in maize-growing regions. However, this scenario would require significantly higher technical oversight and operational management, including consistent biomass feedstock supply, gasifier maintenance, and quality control for both energy and fertiliser outputs. It may necessitate third-party involvement in system operation or technical assistance partnerships, particularly given the limited local technical ecosystem for such systems in Malawi.

Ensuring sustainability under either scenario will require a robust approach to system servicing and maintenance. Battery systems have defined replacement cycles, and gasifiers require regular calibration and cleaning. Without reliable after-sales support, system failures could jeopardise both economic viability and community trust. Partnerships with technology providers, technician training initiatives, or integration with donor-led support platforms will be essential to mitigate this risk.

Across all scenarios, financing solutions must be tailored to the realities of the maize milling enterprises operating in a low-capacity rural environment. Scenario 1, given its relatively modest capital cost (USD 35,000), may be viable through cooperative pooling, local microfinance, or donor microgrants, but its limited environmental performance and continued fossil fuel reliance render it less future-proof. Scenarios 2 and 3, while higher in cost, offer climate-aligned pathways eligible for blended finance. PAYGo or lease-to-own models, commonly used in household solar distribution, could be adapted for productive components such as batteries or inverters, provided adequate guarantees and consumer protection mechanisms are in place. Sector-wide uptake of such models will hinge on scaling enterprise-targeted financial instruments and integrating gender-responsive approaches that explicitly reach rural women-owned productive use ventures.

In summary, this case highlights how decentralised productive energy investments in off-grid Malawi can evolve into integrated service models, supporting not only enterprise growth but also community electrification and agricultural co-benefits. The recommended business model is a hybrid anchor-community approach, rooted in an existing enterprise with strong local legitimacy, and layered with technical and financial innovations that expand its service reach. Embedding such business models within Malawi's evolving gender and energy programming, drawing on experiences from ACRE, RE4A, and community solar entrepreneurship initiatives, would enhance both the inclusivity and sustainability of these transitions. Scaling will require more than capital: it demands integrative design, gender-aware financing, and embedded capacity support tailored to rural realities. Strengthening institutional links between productive use programmes, mini-grid regulation, and rural enterprise financing will be critical to unlocking replication and long-term viability.

8.3.3.5 Case study 5: Leather footwear manufacturing in Nigeria

Case study 5 represents an enterprise that is solely owned by a female entrepreneur and falls under ISIC Division 15 (Manufacture of leather and related products). The enterprise operates across two sites, a production workshop and a retail outlet, serving both local and global markets. Despite grid connectivity, the business faces persistent energy challenges, including frequent power outages, unreliable supply, and high operational costs linked to backup generators and LPG use. These limitations expose the enterprise to productivity losses and price volatility, while reinforcing fossil fuel dependence. In response, two decentralised renewable energy scenarios were developed to evaluate the technical and financial

feasibility of replacing or complementing the current energy configuration. These scenarios explore transitions toward solar PV and battery-based electricity systems, with and without electrification of thermal loads. The analysis is embedded in Nigeria's evolving electrification and business ecosystem, where regulatory reforms, mini-grid development, and targeted financing facilities shape investment outcomes. Gender and inclusion dimensions are also central to this case, given the sole female ownership and the wider national discourse on gender-sensitive energy access and enterprise support. The study provides insights into viable business models and blended financing approaches suited to peri-urban manufacturing enterprises navigating the dual pressures of unreliable grid supply and rising fuel costs.

Scenario context and energy access performance

The energy baseline for this leather goods enterprise combines grid electricity, LPG, and backup generators. Electricity is used across both the production site and retail shop, while LPG powers a Bunsen burner for leather moulding at the production workshop. Two backup generators, a petrol unit for the retail site and a diesel unit for production, are routinely used due to the unreliability of grid electricity. While this hybrid system enables continued operation, it imposes high operating costs, exposes the business to fuel price fluctuations, and generates avoidable GHG emissions. To address these inefficiencies, two alternative energy configurations were modelled. Scenario 1 envisions a decentralised transition to solar PV and battery storage across both sites, while retaining the LPG burner to meet the thermal energy demand. Scenario 1 achieves full independence from the national grid and eliminates the need for petrol and diesel backup, while ensuring a stable, reliable electricity supply. The LPG system is retained, enabling continuity of thermal processing with minimal capital and behavioural shifts. This scenario delivers an MTF tier 4 service level, avoids approximately 15 $tCO_{2\text{-}eq}$/year, and incurs a CAPEX between 122,000 and 135,000 USD, with annual operating costs between 3,000 and 4,000 USD/year.

Scenario 2 deepens the energy transition by fully electrifying all energy uses, including thermal needs. The LPG burner is replaced with electric infrared heating systems, which are technologically appropriate for the 50°C process requirements. This results in full energy autonomy, eliminating reliance on both grid electricity and fossil fuels, while streamlining procurement and operations. Scenario 2 meets MTF tier 5, avoids approximately 15 $tCO_{2\text{-}eq}$/year, marginally higher than scenario 1, though the rounded values appear equivalent. Scenario 2 entails a slightly higher

CAPEX (130,000-143,000 USD) with comparable annual operating costs (3,000-4,000 USD/year). This transition eliminates the logistical and cost burdens associated with LPG, while improving system coherence and sustainability.

As of 2020, Nigeria ranked 131st on the World Bank's Ease of Doing Business Index with a score of 56.9, highlighting persistent barriers to business formalisation, reliable infrastructure, and credit access (The World Bank Group, 2020). The ERI classified Nigeria as having "substantial" regulatory development, with relatively robust frameworks, particularly for mini-grid deployment (AfDB Group, 2022). Meanwhile, the Global Gender Gap Index placed Nigeria at 125th out of 146 countries, with a score of 0.65, indicative of persistent gender inequalities across economic and political domains despite some institutional reforms (World Economic Forum (WEF), 2024). These metrics illustrate both the opportunities and limitations of implementing gender-responsive, decentralised energy transitions in Nigeria's complex regulatory and socio-economic environment.

Enabling environment: Policy, institutional and financial dimensions

Nigeria has developed one of Africa's most comprehensive decentralised energy regulatory frameworks, with clearly defined rules on licensing, tariff setting, grid encroachment compensation, and investor protection (Mission 300 Africa Energy Summit, 2025a; Wearne & Tiwari, 2021). Since the unbundling of the national utility NEPA under the 2005 Electric Power Sector Reform Act, the sector has undergone continuous transformation, marked by the creation of key institutions such as the NERC and the Rural Electrification Agency (REA) (Wearne & Tiwari, 2021). These reforms established a mixed market model with private generation and distribution companies and a publicly controlled transmission operator. While grid expansion remains an important national objective, the unreliability of supply, high technical and commercial losses, and frequent outages continue to challenge energy-intensive enterprises, making decentralised options increasingly attractive (Mission 300 Africa Energy Summit, 2025a; Wearne & Tiwari, 2021). Therefore, NERC's 2017 Mini-Grid Regulation, updated in 2023, remains central to de-risking rural and peri-urban energy investments. A forthcoming National Electrification Strategy and Implementation Plan (NESIP), expected in 2025, is poised to integrate ongoing programmes and reforms into a unified roadmap for universal energy access (Mission 300 Africa Energy Summit, 2025a). Meanwhile, long-term electrification goals are guided by Vision 30:30:30, which seeks to reach 30 GW of installed capacity by 2030, with 30% from renewables (IEA, 2024a). This was updated under Nigeria's Energy Transition Plan

(2021), which now targets 42 GW by 2030, with 6.3 GW expected from decentralised renewable sources.

Tariff structures have been designed to move toward cost reflectivity through the Multi-Year Tariff Order (MYTO), but affordability constraints, particularly in rural and underserved areas, have necessitated capped tariffs for mini-grid operators, typically between USD 0.40-0.50/kWh (Wearne & Tiwari, 2021). Although these ceilings are not always viable for cost recovery, they reflect a pragmatic attempt to balance commercial viability with social inclusion. The 2023 Electricity Act introduced a major regulatory shift by decentralising energy governance, enabling subnational governments to develop state-level electricity markets (Mission 300 Africa Energy Summit, 2025a). This legislative change opens the door for more tailored and context-specific electrification models, particularly in regions with a strong political commitment to decentralised renewable energy.

Clean cooking has emerged as a new policy priority, with the 2024 National Clean Cooking Policy aiming for universal access by 2030 (Mission 300 Africa Energy Summit, 2025a). LPG and improved biomass stoves are prioritised, particularly for rural communities (IEA, 2024a). Clean cooking access is now integrated into broader national electrification plans, creating synergies with solar mini-grid development and LPG distribution platforms.

Nigeria's off-grid landscape is among the most funded in sub-Saharan Africa (Wearne & Tiwari, 2021). The Nigeria Electrification Project, with USD 550 million in capital from the World Bank and AfDB, anchors the country's off-grid strategy through performance-based grants, minimum subsidy tenders, and risk mitigation mechanisms. The National Electrification Project is complemented by a Rural Electrification Fund (REF), which covers up to 75% of capital costs for mini-grids, with specific provisions for productive use components. Additional pilot programmes supported by the EU and GIZ, such as the Mini-Grid Acceleration Scheme and its interconnected variant have further catalysed uptake, targeting commercial viability and productive use linkages (Soni & Kawahara, 2020). Private-led mini-grid projects, including Rensource's 1.3 MW market system in Kano, demonstrate the viability of productive use electrification models when backed by concessional capital. Furthermore, the Central Bank of Nigeria's Solar Connection Facility and the Bank of Industry's Solar Fund have established concessional loan windows with rates as low as 9-10%, targeting solar developers and productive users (Wearne & Tiwari, 2021). Despite these instruments, however, access to local commercial lending remains constrained by stringent

collateral requirements and widespread reluctance to accept solar assets as security (Soni & Kawahara, 2020). As a result, most developers depend on equity or concessional capital from DFIs and international investors. Nigeria's projected universal access target by 2030 will require 23 billion USD in investment, of which 15.5 billion USD is expected to come from private capital (Mission 300 Africa Energy Summit, 2025a). To meet this target, the Federal Government is now formalising least-cost access pathways, licensing reforms, net billing provisions, and a national monitoring and evaluation (M&E) system. These institutional developments could play a pivotal role in improving bankability for decentralised systems, particularly for peri-urban enterprises such as the one in this case study.

Gender considerations within Nigeria's energy sector reflect a dual reality. On one hand, Nigeria is the only ECOWAS country where women represent nearly half (47%) of technical staff within energy institutions (Maduekwe et al., 2019). On the other hand, national energy policies remain largely gender-neutral, with no designated gender focal points or mechanisms within the Ministry of Energy (ECOWAS, 2017). While the ECOWAS Policy for gender mainstreaming in energy access has spurred broader regional awareness, implementation in Nigeria remains uneven. Institutional audits and public awareness campaigns have been initiated, but robust enforcement of gender-responsive energy policy is still lacking (ECOWAS, 2017; Maduekwe et al., 2019).

Nonetheless, several programmes are paving the way for more inclusive energy-enterprise ecosystems. Solar Sister Nigeria has emerged as a flagship initiative, training over 4,000 women entrepreneurs across 30 states in the sale and distribution of solar home systems and clean cookstoves (Schneider & Roche, 2024). The programme provides technical and business training, mentorship through "Sisterhood Groups", and access to zero-interest "Business Booster Loans" up to 200 USD. The approach has led to a fourfold increase in the distribution of productive use appliances by women-owned MSMEs. While these achievements mark progress, the structural challenges facing women in accessing enterprise finance remain acute (Edomah et al., 2021). Gender bias in credit assessments, lack of suitable collateral, and a persistent perception of solar as a non-bankable asset constrain scale-up. To close these gaps, stakeholders have called for more inclusive financial products, tailored enterprise development support, and sustained capacity-building partnerships (Edomah et al., 2021; Maduekwe et al., 2019). Collaboration with women-led cooperatives and intermediary organisations could strengthen access to finance while also facilitating the diffusion of clean energy technologies into gender-diverse entrepreneurial spaces. However, without structural policy

alignment and institutional anchoring, gender inclusion risks remaining peripheral to Nigeria's broader energy transition.

In summary, Nigeria's enabling environment is characterised by a unique blend of progressive regulatory frameworks, robust off-grid investment programmes, and persistent financing and gender equity gaps. For medium-scale enterprises navigating unreliable grid supply, the landscape offers a growing array of tools and incentives, but implementation lags and institutional coordination remain challenges. Unlocking inclusive, decentralised energy transitions will depend on aligning policy ambition with grounded delivery mechanisms, ones that address technical, financial, and social barriers in an integrated manner.

Business model and financing strategy

The energy transition model proposed for this peri-urban leather goods enterprise is anchored in a standalone, entrepreneur-led approach, suited to the operational characteristics and investment profile of the business. The enterprise, solely owned by a female entrepreneur, operates across two sites, a production workshop and a retail outlet, under a single revenue stream generated through the sale of manufactured leather goods. This business model, while established and operationally sound, is relatively undiversified, which limits opportunities for internal cross-subsidisation or demand aggregation that other multi-service or community-integrated models may allow. As such, the financing and operational design of the energy system must be carefully structured to minimise exposure to cashflow volatility and preserve the integrity of the core business.

Both decentralised energy scenarios, scenario 1 (retaining LPG for thermal loads) and scenario 2 (full electrification), offer comparable GHG mitigation (approximately 15 $tCO_{2\text{-}eq}$/year) and investment requirements, with CAPEX ranging from 122,000 to 143,000 USD and annual OPEX between 3,000 and 4,000 USD/year. Scenario 2 offers a higher MTF tier (tier 5) and full energy autonomy by replacing the LPG burner with an electric infrared system. However, given the limited marginal gains in cost or emissions reduction between the two configurations, a unified business model and financing strategy is applicable to both, with scenario 2 offering a more streamlined and fuel-independent long-term option.

The core model remains a decentralised, standalone solar PV system deployed across both enterprise sites, configured to ensure full operational reliability in the

face of unreliable grid access and eliminate dependency on diesel and petrol generators. Given the business's urban location, surplus energy distribution to surrounding households, unlike in rural village-based enterprises, is not a primary opportunity, as neighbouring consumers are likely already connected to the national grid. Net metering was initially considered to monetise excess electricity; however, the lack of a functional regulatory framework renders this option currently unviable. Future developments under the 2023 Electricity Act and state-level regulatory autonomy may eventually enable feed-in mechanisms or peer-to-peer trading models, but these remain speculative at present.

In the absence of energy-related service diversification, the enterprise will rely on its existing income stream to recover the costs of the energy system. This constraint heightens the need to closely align capital investment with revenue stability and the enterprise's ability to absorb financial risk. Structured financing solutions should therefore prioritise low repayment pressure, transparent amortisation schedules, and protection of working capital to ensure long-term viability. Given the enterprise's moderate scale and relatively stable, though not highly diversified, income base, PAYGo or lease-to-own models may not be optimal unless specifically adapted to accommodate irregular revenue flows and context-specific repayment timelines. Instead, the enterprise would be better served by a blended finance package that integrates multiple instruments: RBF to reduce CAPEX, concessional loans for system procurement, and grant-funded technical assistance to support energy transition planning and operational adaptation. Several platforms could facilitate this approach. Concessional debt instruments such as the Central Bank of Nigeria's Solar Connection Facility (10% interest rates) and the Bank of Industry's Solar Fund (9% interest rates) provide viable lending channels, particularly when layered with RBF to lower the effective investment cost (Wearne & Tiwari, 2021). GIZ-backed productive use pilots offer tested models for bundling finance with enterprise training and system design, crucial for ensuring that capital is not only deployed, but translated into sustainable impact (Soni & Kawahara, 2020). Additionally, gender-focused initiatives like Solar Sister may offer replicable delivery elements, namely capacity-building, mentoring, and simplified loan access, that could be adapted through enterprise accelerators or donor-funded pilots. The entrepreneur's profile also aligns with Nigeria's growing ecosystem of gender-responsive enterprise support, even as credit constraints for women-led MSMEs remain significant due to biases in collateral requirements and under-recognition of energy assets in financial risk models (Edomah et al., 2021). In this context, partnerships with blended finance initiatives or impact investors targeting gender-lens portfolios may offer a viable path to capitalisation, provided the

enterprise is supported through tailored business development services and technical assistance. Operationally, it must be ensured that the energy system is fully aligned with production cycles, without introducing complexity that could burden the entrepreneur or disrupt the enterprise's workflow. Basic training in energy system operation, safety, and battery management will still be essential to ensure that the enterprise can manage the new system effectively without external reliance. Bundled service agreements with solar providers or cooperative maintenance networks could be explored to secure long-term technical support and protect against performance degradation.

In conclusion, the most viable business model for this peri-urban leather manufacturing enterprise is a modular, entrepreneur-led, standalone solar PV system financed through a layered, blended finance approach. The enterprise's single revenue stream heightens sensitivity to investment risk, requiring financing models that limit exposure and prioritise cashflow preservation. While scenario 2 offers a more resilient and cleaner long-term pathway, both scenarios are technologically and financially feasible under Nigeria's current enabling environment. Successful replication will depend not only on capital mobilisation but also on the integration of technical training, gender-responsive financial tools, and targeted enterprise support that aligns energy transitions with broader business resilience and women's economic empowerment in the clean energy sector.

8.3.3.6 Case study 6: Textile manufacturing in Tanzania

Case study 6 analyses clean energy transition strategies for women-led cooperatives engaged in textile manufacturing in Tanzania, classified under ISIC Division 13 (Manufacture of textiles). It evaluates the technical and financial viability of alternative energy solutions designed to reduce reliance on conventional fuels, mitigate emissions, and strengthen enterprise resilience. The analysis draws on scenario-based modelling of 50 women entrepreneurs operating under cooperative structures, offering a representative sample of decentralised, small-scale industrial operations in Tanzania's urban and peri-urban settings. The case is situated within a national policy landscape that has prioritised universal energy access, clean cooking, and gender equity, but where implementation gaps persist, particularly in extending productive use solutions to women's cooperatives. This analysis contributes to identifying context-specific business models and financing approaches that can support scalable transitions for women-led productive use enterprises navigating cost, capacity, and infrastructure constraints.

Scenario context and energy access performance

The base case of case study 6 relies on grid electricity and traditional biomass (charcoal and firewood), which together generate high operational costs and significant GHG emissions, while exposing businesses to unreliable service and fuel price volatility. Scenario 1 introduces a low-carbon transition by shifting entirely to grid-based electricity for ironing and maintaining LPG for thermal loads. This approach reduces emissions substantially and requires only moderate capital investment (USD 4,000) but continues to rely on fossil fuel inputs with relatively high operating costs reaching 37,000 USD/year. While scenario 1 eliminates reliance on traditional biomass, its dependence on LPG and grid electricity makes it vulnerable to price and supply instability.

Scenario 2 assesses a more ambitious transition involving biomethane derived from slaughterhouse wastewater. The sub-scenarios differ in terms of infrastructure complexity, notably the addition of gas compression and cylinder storage in scenarios 2B and 2C, which allow for fuel bottling and decentralised distribution. Although these configurations lead to progressively higher CAPEX, they also offer greater GHG mitigation (240 $tCO_{2\text{-eq}}$ avoided/year) compared to scenario 1. The investment required ranges from 628,000 to 1,043,000 USD, with OPEX between USD 18,000 and 20,000. Despite their environmental advantages, these scenarios face economic feasibility challenges without strong institutional or donor support, especially given the need for advanced infrastructure and coordination with municipal slaughterhouse operations.

Scenario 3 represents the most balanced approach, involving decentralised anaerobic digestion of MSW to produce biogas. This configuration achieves full energy autonomy for cooperative operations, incurs moderate annual operating costs (25,000 USD/year), and delivers the highest emissions reduction (257.53 $tCO_{2\text{-eq}}$ avoided/year), with a moderate capital investment of USD 114,000. The model achieves the highest tier under the MTF among all enhancement scenarios (tier 5), marking a full transition from fossil-based fuels and unreliable grid inputs. Moreover, the utilisation of local waste streams aligns with circular economy principles and presents potential co-benefits for urban waste management, particularly in dense settlements where municipal services are under pressure.

The enabling context for these transitions remains mixed. Tanzania ranks 141st on the 2020 World Bank Ease of Doing Business Index, with a low score of 54.5, reflecting challenges related to regulatory predictability and financial access (The

World Bank Group, 2020). However, the country scores relatively well under the Business Ready diagnostic, with a regulatory framework score of 65, a public services score of 51.56, and an operational efficiency score of 62.15, indicating a moderately robust institutional environment for enterprise formalisation and infrastructure access (The World Bank Group, 2024a). Tanzania also maintains a "substantial" regulatory development status on the ERI, signalling an improving institutional landscape for energy access, including decentralised energy (AfDB Group, 2022). On gender equity, Tanzania ranks 54th on the Global Gender Gap Index (2024), with a score of 0.734, the highest in the dataset, indicating a relatively strong platform for gender integration, especially in rural and cooperative-based interventions (World Economic Forum (WEF), 2024). These metrics point to both enabling opportunities and operational constraints that will shape the bankability, replicability, and sustainability of cooperative clean energy models across Tanzania.

Enabling environment: Policy, institutional and financial dimensions

Tanzania presents a dual narrative in its decentralised energy and gender inclusion landscape: one of ambitious national targets and institutional maturity, but also regulatory fragmentation and persistent barriers to last-mile implementation. Over the past decade, the country has made remarkable strides in electrification, increasing national electricity access from under 15% in 2011 to nearly 80% by 2020, mainly due to an aggressive grid expansion programme covering all 12,318 villages (Mission 300 Africa Energy Summit, 2025b). Yet household-level connectivity lags, particularly in rural and peri-urban areas, where affordability, weak infrastructure, and unreliable service quality continue to constrain the effective use of electricity. These limitations make decentralised energy systems, especially those oriented toward productive use, an increasingly critical complement to grid-based supply.

Tanzania was an early mover in the East African mini-grid sector (GOGLA, 2021d; Soni & Kawahara, 2020). By 2018, more than 200 renewable and hybrid mini-grids had been deployed, supported by a relatively enabling Small Power Producer (SPP) framework and donor-backed capital. However, subsequent regulatory shifts have introduced uncertainty. The 2018 requirement for full licensing of mini-grids under 1 MW, formerly only registered, increased compliance burdens for small developers (Soni & Kawahara, 2020). Moreover, although EWURA permits cost-reflective tariffs, developers of Very Small Power Producers (VSPPs) under 100 kW now require explicit tariff approvals, creating

friction in an otherwise dynamic sector. Regulatory clarity around grid arrival rules and integration of mini-grids into national electrification planning also remains limited, further deterring investment (GOGLA, 2021d; Soni & Kawahara, 2020).

Nonetheless, the institutional landscape remains relatively robust. The Ministry of Energy retains overall sector oversight, supported by EWURA (regulation), the Rural Energy Agency (REA), and TANESCO (utility operations) (Soni & Kawahara, 2020). REA has proven pivotal in mobilising RBF and concessional capital. For instance, the Renewable Energy Companies Credit Line established by REA, capitalised with 10 million USD, facilitates debt financing for rural renewable energy firms. Tiered RBF programmes co-funded by DFID and SIDA offer grants of USD 300-600 per household connection, scaled to service levels. Tanzania has also launched the Green Economy Recovery Fund (GERF), implemented by SNV and supported by BMZ, which provides results-based subsidies of up to 400,000 € for off-grid solar enterprises (GOGLA, 2021d). These instruments contribute to a growing toolbox for decentralised energy finance, though implementation bottlenecks and delayed disbursement remain concerns for developers and cooperatives alike.

From a macro-financial perspective, Tanzania's targets remain bold but underfunded. The government aims to mobilise 4 billion USD in private investment to meet electrification and clean cooking goals by 2030 (Mission 300 Africa Energy Summit, 2025b). This ambition is supported by planned policy instruments such as the IPP procurement framework (by 2026), competitive power market design (by 2027), and new rural energy master plans. However, structural obstacles remain. These include inconsistent tax treatment for solar components, burdensome procurement rules, and tariff-related disputes in the mini-grid sector (GOGLA, 2021d; Soni & Kawahara, 2020). A coherent national electrification framework integrating grid, mini-grid, and standalone systems is still under development, and the absence of such coordination limits the bankability of decentralised energy projects, especially in peri-urban and cooperative-led contexts.

In parallel, the clean cooking sector is undergoing a major policy transformation. The 2024 National Clean Cooking Strategy aims for 80% clean cooking access by 2034, underpinned by result-based subsidies, tax exemptions, and support for improved cookstoves, LPG, electric cooking, and biogas technologies (Mission 300 Africa Energy Summit, 2025b; The United Republic of Tanzania & Ministry of Energy, 2024). Importantly, this strategy includes a dedicated gender component, mandating women's inclusion in technology

distribution, leadership, and policy implementation. This reflects Tanzania's broader trend toward gender mainstreaming in the energy sector, as also articulated in the 2015 National Energy Policy and the SEforALL Gender Action Plan (Ngoo & Kooijman, 2020). The Gender and Energy Strategy (2012), though under review, continues to guide REA's planning and implementation processes, with practical interventions piloted under the Scaling-up Renewable Energy Programme (SREP). These include targeting women-headed households for energy connections and training women technicians for solar and clean cooking installations.

Despite these progressive frameworks, institutional capacity remains uneven. While gender desks and committees have been established within the Ministry of Energy, they lack formal mandates to shape energy policy or planning processes (Ngoo & Kooijman, 2020). Moreover, there is no national framework for gender-responsive budgeting across the energy sector. The evidence base suggests that without deliberate and targeted action, men continue to dominate access to productive electricity uses (Pueyo, Carreras, et al., 2020). In addition to this, there are significant gender disparities in financial access: while women are more likely to seek and take out loans (22% vs. 17% for men), they are less likely to own bank accounts or receive grants. However, projects implemented under ENERGIA's research programme in Tanzania have demonstrated the transformative impact of gender-responsive energy approaches, including shifts in intra-household decision-making, increased income generation, and the reallocation of household roles when women gain access to productive energy assets and access to financial resources (Ngoo & Kooijman, 2020; Pueyo, Carreras, et al., 2020).

In summary, Tanzania's enabling environment is shaped by early leadership in decentralised energy, ambitious clean cooking and electrification targets, and institutionalised gender frameworks. Yet the operational reality reveals friction between policy and practice. For women-owned enterprises and cooperatives navigating the energy transition, access to concessional finance, RBF, and targeted training support can offer viable pathways. However, these must be matched by policy coherence, regulatory streamlining, and active enforcement of gender and energy equity principles to ensure that decentralised transitions do not merely reproduce existing structural inequalities. The potential is evident, but realisation will depend on sustained implementation momentum and inclusive policy design.

Business model and financing strategy

The scale, complexity, and collective structure of this case study, anchored in a network of 50 women entrepreneurs supported by a reference entrepreneur, requires a carefully designed business model that goes beyond traditional, individualised delivery mechanisms. Although the reference entrepreneur plays a pivotal catalytic role by providing technical mentorship and serving as a local anchor of trust, the realisation of any of the enhanced energy scenarios demands both institutional support and access to blended financing mechanisms. The capital intensity of the biomethane and decentralised biogas options (scenarios 2 and 3), far exceeds the personal investment capacity of the reference entrepreneur, necessitating a cooperative or third-party-led implementation approach.

Given these dynamics, a layered anchor-community model emerges as the most viable and context-appropriate structure. In this model, the reference entrepreneur acts as the technical and managerial nucleus around which a broader energy service provision network is structured. Her role would include managing the interface between the cooperative and energy service providers, facilitating access to capacity building, and supporting business development. However, ownership and financing responsibilities would be distributed across a broader consortium, comprising the women's cooperative, a third-party energy developer or NGO, and aligned financial intermediaries. This model allows for risk-sharing while also leveraging the trust-based social capital already embedded within the group. The ownership and delivery structure could be formalised as a hybrid cooperative-third-party model, in which the cooperative holds partial equity or leasehold rights over decentralised energy infrastructure, while a third-party implementer, such as a social enterprise or NGO with energy deployment experience, handles technical design, installation, and maintenance. Such a structure helps overcome the capacity gaps often faced by grassroots organisations while allowing for a gradual transfer of operational control as local technical competencies are built over time.

Each of the three modelled energy scenarios offers different implications for this hybrid structure. Scenario 1, based on grid electricity and LPG, requires the lowest upfront investment (USD 4,000) and potentially retains a single cooperative revenue stream from textile sales. Its affordability and compatibility with existing practices make it an attractive entry point, especially for cooperatives with limited financial and technical capacity. The primary challenge lies in financing the grid connection fees and initial LPG access. Here, Tanzania's Rural Energy Fund (REF), administered by REA, provides a potential avenue for subsidy support (Soni &

Kawahara, 2020). The REF offers capital grants of up to USD 600 per household or productive use connection, though eligibility criteria should be expanded to explicitly include small-scale women's cooperatives engaged in textile manufacturing in urban and peri-urban areas. On the thermal side, LPG support remains narrowly targeted to household cooking. As such, it is critical that Tanzania's National Clean Cooking Strategy (2024-2034) evolve to recognise productive uses of LPG in non-domestic sectors, such as textiles, and integrate financing and subsidy mechanisms accordingly.

Scenario 2 envisions a transition to compressed biomethane sourced from slaughterhouse wastewater, involving significantly higher capital costs (USD 628,000-1,043,000) and requiring the introduction of 200-bar pressurised cylinders. This advanced configuration achieves full fossil fuel substitution and substantial GHG mitigation, but its feasibility depends on third-party implementation and a robust financing architecture. In this case, the cooperative could enter into a long-term energy purchase agreement with a biomethane supplier, potentially a municipal enterprise, social investor, or circular economy initiative. The reference entrepreneur could serve as the project liaison, helping structure agreements and support uptake, but the risk and responsibility for infrastructure deployment would rest with the service provider. Blended financing involving concessional loans, donor-backed RBF, and carbon credit monetisation could be explored to cover capital costs, while performance-linked grants under Tanzania's REF or the Renewable Energy IPP Procurement Programme (by 2026) could provide additional incentives (Mission 300 Africa Energy Summit, 2025b).

Scenario 3, based on decentralised biogas production from MSW, presents the most balanced option in terms of financial viability, technical autonomy, and environmental benefits. With a CAPEX of 114,000 USD and annual operating costs of 25,000 USD/year, this configuration achieves the highest GHG savings (258 $tCO_{2\text{-eq}}$ avoided/year). The cooperative would serve as both an anchor client and a partial contributor to system development, offering land, labour, or in-kind materials. While a specialised biogas enterprise or local NGO would initially lead the implementation and technical maintenance, operational responsibilities could be gradually transferred to cooperative members. A phased training approach would ensure that women entrepreneurs within the cooperative build the necessary skills in system O&M over time, strengthening local ownership and long-term sustainability. This hybrid cooperative-third-party model is especially appropriate here, enabling risk-sharing and professional system upkeep. Given the system's decentralised nature and circular resource logic, it could be eligible for funding

under the Renewable Energy Companies Credit Line (GOGLA, 2021d). Additional support could be sourced through the Green Economy Recovery Fund (GERF), which offers results-based incentives to renewable energy firms. With the cooperative model already proven viable and trusted, donors and government partners should consider earmarking specific RBF windows for women-led cooperatives in the manufacturing and textile sectors.

A cross-cutting financing challenge across all scenarios is the current emphasis of Tanzania's mini-grid, LPG, and biogas support programmes on household cooking or residential electrification (Mission 300 Africa Energy Summit, 2025b; The United Republic of Tanzania & Ministry of Energy, 2024). Productive use in non-cooking sectors, such as textiles, remains underrepresented in eligibility criteria, leading to inadvertent exclusion from existing financial mechanisms. To remedy this, national strategies should explicitly recognise the productive use of clean energy in MSMEs and cooperatives. Revising sectoral policies to include a productive use lens, coupled with tailored grant, credit, and lease-to-own schemes, would significantly broaden the reach and equity of decentralised energy transitions.

Operational sustainability also requires consideration. For the decentralised systems modelled here, long-term servicing and replacement cycles pose a risk if not embedded into the financial model. Leasing arrangements with third-party servicing providers, bundled warranty packages, or cooperative-led maintenance pools could be structured to provide ongoing support. Where possible, technical training should be provided to select cooperative members, enabling gradual internalisation of basic maintenance tasks and reducing external dependency.

In conclusion, this case study points to a scalable model for inclusive energy access that builds on cooperative agency, decentralised technology, and catalytic mentorship from a trusted reference entrepreneur. Whether through grid-electricity and LPG, compressed biomethane, or decentralised biogas, the business models must be structured around shared accountability, third-party operational support, and blended finance. Recognising the cooperative's role not just as energy consumers but as active participants in Tanzania's green and gender-responsive transition will be essential to ensure long-term success. The policies, financing tools, and regulatory instruments are gradually taking shape; what remains is to connect them into coherent, context-responsive pathways that support entrepreneurial agency, energy inclusion, and climate resilience in tandem.

Following the individual assessments of the six case studies, the next section examines what broader lessons can be drawn. It synthesises cross-cutting insights, reflects on the interplay between enterprise realities and institutional readiness, and interrogates what constitutes an appropriate business model or financing approach under varying conditions of risk, policy alignment, and gender inclusion.

8.4 Discussion

The discussion section shifts the analytical focus from the specificity of individual enterprises to a comparative, cross-case lens. Having examined six distinctive scenarios, each grounded in the operational realities of women-owned or gender-inclusive enterprises, this section brings these cases into structured dialogue. It moves from the granular to the general, asking not what worked in one place, but what patterns emerge across contexts, and what these patterns reveal about designing scalable, equitable energy solutions. At the heart of this analysis lies a core research question: ***what kinds of business models and financing schemes are most appropriate to support women-owned enterprises under enhanced energy access scenarios in diverse African contexts?***

Each case was analysed through a shared methodological lens integrating energy performance indicators, institutional diagnostics, and gender-aware financing frameworks. Yet the diversity in enterprise types, ownership models, technology configurations, and policy environments reveals no single formula for success (Bose, 2011; Mbate & Fall, 2025). Instead, the analysis highlights patterns and tensions that offer valuable lessons for donors, policymakers, and practitioners seeking to operationalise equitable energy transitions.

First, a key finding across all cases is the importance of anchor enterprises in structuring viable decentralised energy configurations (Dibaba et al., 2023; Fajardo et al., 2025; Falchetta et al., 2022). In Ghana, Kenya, and Malawi, enterprises engaged in food processing could assume this role due to their integration in local value chains and the presence of stable energy demand. Nigeria presents a different case, where a peri-urban leather manufacturing business is grid-connected, but its single revenue stream and lack of surrounding energy-deficient users constrain service diversification and aggregation potential. Tunisia similarly highlights spatial limitations: the agricultural processing site's physical isolation makes it difficult to share infrastructure with other users or co-locate energy services. In contrast, the Tanzania case reveals a cooperative model built around 50 women entrepreneurs, demonstrating how decentralised systems can be jointly structured

to serve diffuse yet coordinated demand, especially when supported by a catalytic reference entrepreneur. In all contexts, the ability of anchor enterprises with a stable demand to coordinate energy use and interface with technical providers is fundamental to unlocking bankability and scalability.

Second, the financial architecture of successful models consistently relies on some form of blended capital (Fajardo et al., 2025; Nsakaza & Chilipaine, 2025). Across Ghana, Kenya, Malawi, and Tanzania, combinations of donor-backed subsidies, concessional debt, and community contributions are required to make systems viable. Even in relatively more developed regulatory settings, such as Tunisia and Nigeria, capital market gaps persist, particularly in mobilising finance for MSMEs. The Ghana case exemplifies the importance of RBF and infrastructure subsidies for NGOs serving low-income users. Nigeria and Tunisia demonstrate how concessional loan windows, such as Prosol-Elec, the FTE, or the Bank of Industry's Solar Fund, can de-risk private capital, but also highlight limitations in reaching women-owned small- and micro-sized enterprises due to high collateral demands and asset misclassification. Kenya and Malawi provide insight into how layered financing, including equipment leasing and cooperative pooling, can be adapted to enable energy-as-a-service models, though these remain contingent on technical assistance and regulatory clarity. In all cases, risk-sharing instruments (e.g. credit guarantees, subordinated debt, carbon finance) remain underused but critically needed to attract commercial co-investment, particularly in high-CAPEX, high-impact scenarios.

Third, the degree to which energy transitions support enterprise resilience and long-term productivity depends on the integration of non-financial enablers (Mosetlhe et al., 2025; Pueyo et al., 2019; Pueyo & Maestre, 2019; Scott, 2017). Capacity building, market access, and gender-sensitive enterprise development are cross-cutting conditions for success, yet often peripheral in energy finance schemes. In Ghana, the NGO's ability to aggregate products and extend storage services could be as important as the energy system itself. In Kenya, value-added integration, such as digestate fertiliser from biogas, could transform energy into an input for circular agricultural systems. In Tanzania, the reference entrepreneur's role as a trusted mentor and technical facilitator is indispensable for translating infrastructure into collective empowerment. However, such ecosystem elements are frequently neglected in investment pipelines and national policy frameworks, which focus predominantly on hardware delivery and quantitative access metrics. Addressing this requires a reframing of productive use not merely as electricity consumption but as a nexus of skills, services, and markets (Pueyo & Maestre,

2019; Scott, 2017). Although development partners, DFIs, and national planning agencies started to incorporate these broader dimensions into programme design and impact assessment frameworks, they can do more to reach scale.

Fourth, policy frameworks in key sectors often fail to keep pace with the evolving energy needs and innovations emerging at the enterprise level, particularly in aligning productive use priorities with gender-responsive strategies (Pueyo & Maestre, 2019). For instance, clean cooking strategies in Malawi and Tanzania tend to narrowly focus on household energy use, overlooking the critical role that fuels such as LPG, biogas, and other thermal energy carriers play in productive use sectors, including small-scale agri-processing and textile production (Republic of Malawi & Ministry of Natural Resources, 2017; The United Republic of Tanzania & Ministry of Energy, 2024). These strategies often frame clean cooking solely in terms of domestic health and gender outcomes, with limited recognition of enterprises that use the same energy carriers for commercial purposes. As a result, women-owned businesses that rely on thermal loads for production are systematically excluded from clean cooking financing, policy incentives, and infrastructure planning. This blind spot undermines efforts to scale productive use and reinforces an artificial divide between household and enterprise energy needs, despite their shared reliance on similar fuels and technologies. Similarly, many mini-grid and off-grid support schemes exclude non-domestic users by default or offer tariffs and subsidies misaligned with industrial use patterns. Nigeria's relatively advanced regulatory framework for mini-grids is notable, but its lack of gender mainstreaming limits the potential of women-owned enterprises to access and scale decentralised systems (Edomah et al., 2021). Tunisia provides a positive counterpoint, where subsidy frameworks have begun to evolve toward productive use, though inconsistently across sectors (EDAMA, 2022; ESCWA, 2022, 2023). This underscores the need for more deliberate integration of productive use and gender into energy planning, regulation, and financing mechanisms. As demonstrated in all six cases, MSMEs are critical users and enablers of decentralised energy systems but are rarely central to policy design.

Fifth, macroeconomic and institutional stability play a determining role in scaling business models (Bukari et al., 2021; James et al., 2025; Kapole et al., 2023; Lambe et al., 2024; Peters et al., 2019). In high-risk environments, exchange rate volatility, inflation, and public budget constraints complicate capital mobilisation and long-term financial viability. In Nigeria, relatively mature financial tools exist but are unevenly accessible, particularly for women (ECOWAS), 2017; Maduekwe et al., 2019). In Tunisia, while public finance is available, institutional bottlenecks

and legacy energy subsidies distort incentives and limit private participation (Calì & Zitouna, 2023; Hamedi et al., 2021). Across all contexts, there is a pronounced need for currency risk mitigation tools, long-term maintenance planning, and stronger institutional links. The presence of vocational training networks, enterprise support centres, or women's associations, as seen in Tunisia, Ghana, and Tanzania, could often be a decisive factor in whether enterprises could absorb and operationalise energy transitions. Future programme design should formalise such linkages, embedding energy delivery into broader economic development ecosystems rather than treating it as a standalone infrastructure challenge.

To distil these comparative case insights, Figure 59 presents the five cross-cutting lessons derived from the analysis. These findings offer strategic guidance for donors, planners, and practitioners designing gender-responsive business models and financing schemes for inclusive energy transitions.

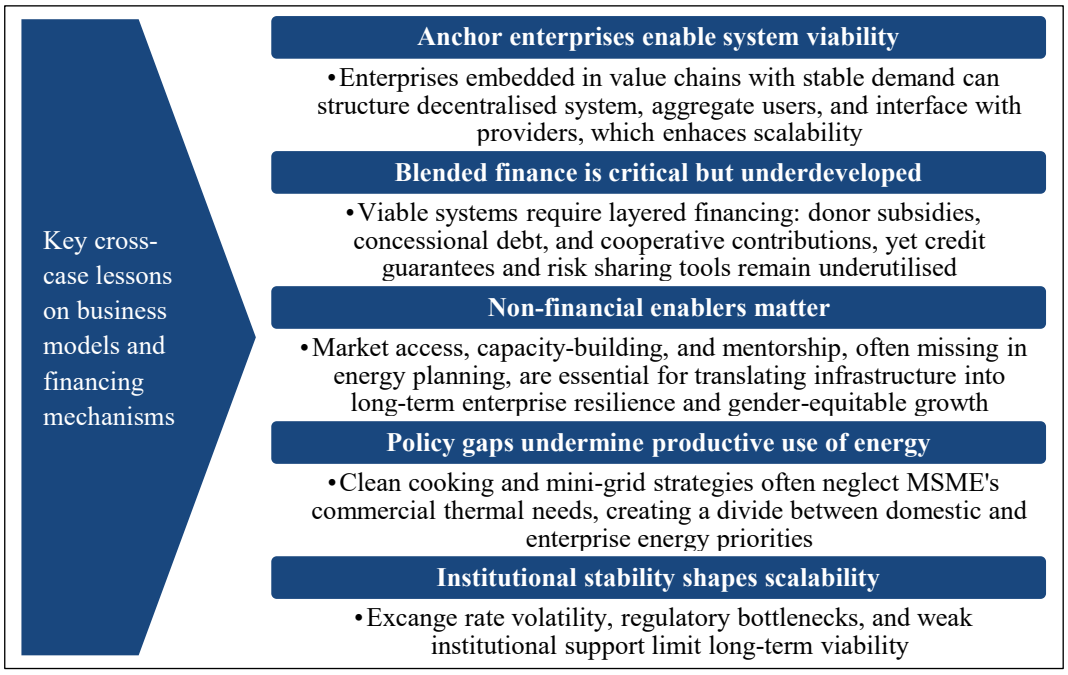

Figure 59. Cross-case lessons on business models and financing for inclusive energy transitions

In conclusion, the case studies in this study demonstrate that decentralised energy transitions, when carefully aligned with enterprise realities and embedded in local institutional ecosystems, offer a powerful pathway towards inclusive and environment-friendly rural development. While no single model applies

universally, common principles emerge: anchor-based system design, blended finance, gender-responsive planning, and integrated service delivery are central pillars of success. However, these are not sufficient in isolation. Realising scale and sustainability requires deliberate investment in ecosystem infrastructure, including financial and institutional instruments as well as capacity building to enable energy to catalyse broader economic transformation. The policy challenge lies not only in expanding access but in enabling productive and equitable energy use. For development partners, financiers, and governments alike, this calls for a shift from isolated pilots to coordinated, multi-sectoral strategies that bridge the divide between energy provision and enterprise resilience. Only through such systemic approaches can energy transitions serve as engines of inclusive development.

8.5 Conclusions

This chapter examined how business models and financing schemes can support clean energy transitions in women-owned enterprises across Africa. The findings underscore that while decentralised technologies offer potential for enterprise resilience and decarbonisation, success depends on aligning delivery models, financing structures, and local gendered realities. No one-size-fits-all model emerged; rather, viable approaches included blended finance, community-based models, cooperatives, and lease-to-own schemes, each adapted to enterprise size, risk profile, and market conditions.

Gender-responsive finance remains underdeveloped, with barriers such as collateral demands and sectoral exclusion limiting inclusive energy access. Yet, when coupled with regulatory clarity and stable revenue streams, inclusive financing can catalyse productive use transitions.

The analysis bridges policy-level ambition with grounded enterprise scenarios, highlighting financially viable and contextually relevant pathways. However, the models proposed remain indicative, not prescriptive. Ultimately, scaling productive energy access requires not only capital and infrastructure but also inclusive governance, tailored risk instruments, and embedded enterprise support. The final chapter of this thesis reflects on the broader implications of these findings, situating them within the wider discourse on gender-equitable energy transitions and outlining pathways for future research, policy, and investment.

Chapter 9

9. Discussion and conclusions – What are the implications of gender-focused energy research for inclusive energy policy, finance, and enterprise support?

9.1 Summary of findings

This research set out to investigate the gendered dynamics of productive energy use among MSMEs in multiple African countries, adopting an exploratory, depth-oriented approach to capture nuanced realities, with a focus on how clean energy transitions can be effectively financed and delivered in women-owned enterprises. The analysis was guided by seven interrelated research questions, which together explore the multiple dimensions of sustainable energy access, productive use and gender-responsive analysis. The findings across all chapters point to a critical shift: from treating gender and energy as parallel domains to understanding them as mutually constitutive forces within development planning. What follows is a synthesis of the main findings, organised around each research question. This is complemented by a critical reflection on the implications for inclusive policy design, targeted investment, and enterprise support. The chapter concludes with an outlook that highlights future research directions and practical pathways for advancing gender-responsive energy transitions.

RQ1: Which African countries and industry sectors offer the most promising empirical grounds for investigating the gendered patterns of productive energy use within MSMEs?

Chapter 4 identified seven countries, Egypt, Ghana, Kenya, Malawi, Nigeria, Tanzania, and Tunisia, as high-priority contexts for analysis, based on a dual selection process incorporating MSME density and women's enterprise activity. The food processing and textile sectors were selected for their dual relevance: they are among the most female-dominated MSME sectors in Africa and simultaneously rely on energy-intensive production processes. However, the analysis also revealed severe data fragmentation, particularly for informal enterprises and disaggregated thermal energy use, highlighting an enduring knowledge asymmetry that complicates gender-sensitive energy planning.

RQ2: To what extent does the gender of the ownership structure influence energy access and productive uses in MSMEs?

Chapter 5 applied a five-category ownership typology to analyse gender-related patterns in energy access and use, with a gender-disaggregated comparison possible only in the Nigerian sample. The results suggest that sole female-owned enterprises face more pronounced constraints in productive energy access than male-owned or gender-diverse enterprises. These include lower levels of energy diversification, higher per-unit energy costs, greater under-reporting of thermal demand, and weaker awareness of energy expenditures. While these findings are context-specific, they echo regional trends identified in the literature, which show that women entrepreneurs often operate in lower energy-intensity sectors, have limited access to finance and appliances, and face compounded challenges due to informal business status and social norms restricting decision-making and mobility. Together, these results underline the need for energy access interventions that account for ownership structure and explicitly support the distinct capacities and constraints of women-owned MSMEs.

RQ3: What are the key characteristics of energy access for productive use among women entrepreneurs? And RQ4: What barriers and drivers influence women entrepreneurs' adoption of renewable energy technologies?

Drawing on primary data obtained through face-to-face interviews, Chapter 6 applied the World Bank's MTF to show that energy access among women-owned enterprises often remains at tiers 1-3, especially in sub-Saharan contexts, while relatively better performance in North African settings coexists with persistent gendered constraints. Women's adoption of renewable energy technologies is constrained less by outright refusal and more by affordability barriers, credit exclusion, and technology-service misalignments. However, when given space to

articulate needs, women demonstrate high awareness of trade-offs and readiness to co-invest in systems that align with their business opertaions. This underscores the value of participatory, demand-driven approaches over supply-led technology rollouts.

RQ5: How can clean energy technologies be configured to meet the productive energy needs of women-owned enterprises? And RQ6: What techno-economic and environmental trade-offs arise when evaluating energy transition scenarios at the enterprise level?

Chapter 7 provided scenario-based assessments for six case studies across diverse contexts, combining NPC, CAPEX and annual operating cost calculations, MTF tier upgrades, and GHG avoidance metrics. The results demonstrate that both grid-connected and decentralised renewable energy configurations, including stand-alone solar PV systems, solar PV integrated with net metering, solar PV-battery-diesel hybrids, and biomass-derived thermal solutions such as biogas, biomethane, and syngas, as well as LPG-based systems, can elevate enterprises to a minimum of tier 3 on the MTF for energy access, with many scenarios achieving tier 4 or tier 5 performance. Yet each scenario involved trade-offs: systems with higher environmental gains often carried elevated capital costs or technical complexity, requiring clear revenue structures and maintenance pathways to be viable.

RQ7: What kinds of business models and financing schemes are most appropriate to support women-owned enterprises under enhanced energy access scenarios in diverse African contexts?

Chapter 8 demonstrated that viable energy transitions require blended, context-specific configurations rather than one-size-fits-all delivery models. Across case studies, successful approaches included anchor-business-community designs, cooperative ownership, lease-to-own mechanisms, and third-party delivery models. Financing strategies combined concessional capital, RBF, and cooperative pooling. However, persistent capital access barriers remain for women entrepreneurs, driven by collateral demands, asset misclassification, and credit information gaps. Gender-responsive finance remains peripheral to most national schemes, limiting the uptake and scale of otherwise viable models.

Together, these findings confirm that technological potential alone is insufficient for advancing gender-equitable energy access. What matters equally, if not more, are the institutional arrangements, financing architectures, and policy

environments that determine how enterprises can access and operationalise these technologies. This research contributes a rare, empirically grounded view of these interconnections at the enterprise level, offering both diagnostic insights and implementation pathways for sustainable development.

9.2 Implications for inclusive energy policy, finance, and enterprise support

The findings of this research point to a fundamental insight: While clean energy solutions, including both decentralised and grid-tied configurations, offer clear technical viability, their scalability and equity outcomes depend on how they are embedded within regulatory frameworks, capital markets, and enterprise ecosystems. This section distils the cross-cutting implications for energy policy, financing architecture, and business support mechanisms, drawing on both the empirical case studies and broader scholarly debates.

Energy policy must centre productive users and mainstream gender beyond household energy use

Despite increasing attention to distributed energy systems in national electrification strategies, productive users, especially women-owned enterprises, remain peripheral in both policy language and implementation (Clancy & Dutta, 2005; Dutta et al., 2017; Pueyo et al., 2019; Pueyo & Maestre, 2019). Additionally, the presented case studies from Malawi and Tanzania highlight that clean cooking programmes, for example, are overwhelmingly designed for domestic settings, with limited applicability to enterprises using thermal energy for commercial purposes. This artificial separation between household and enterprise energy needs has significant consequences: it systematically excludes women entrepreneurs from infrastructure planning, technology subsidies, and tariff design. Integrating productive use into national energy frameworks must begin with reframing women not as passive consumers, but as central economic actors whose energy needs straddle domestic and commercial boundaries. Policies should explicitly link productive use targets to gender equity goals, using differentiated support instruments for enterprise-focused energy demand.

Financing strategies must go beyond microfinance and mainstream blended capital approaches

The financing gap faced by women-owned MSMEs is not simply one of credit access; it is a structural mismatch between the size, risk profile, and return expectations of these enterprises and the instruments available to them (Ferreri et al., 2022; Ruggles et al., 2019). Across all six case studies, viable financing scenarios require a blend of capital types: concessional loans, RBF, grant-based support, and cooperative pooling. Traditional microfinance often fails to meet the scale or time horizon required for energy infrastructure investment, while commercial finance remains risk-averse and inaccessible to most women-owned businesses due to collateral demands and credit history gaps. A new financing architecture is needed, one that combines capital layering, credit guarantees, and results-based disbursement. As demonstrated in Ghana and Kenya, donor-backed guarantees and co-investment platforms can play a catalytic role in unlocking private sector participation. However, these mechanisms must be designed with explicit gender inclusion criteria to avoid reinforcing existing disparities.

Business models should be tailored to anchor users, shared infrastructure, and circular value creation

The success of distributed clean energy transitions, including both off-grid and grid-tied solutions, depends on the ability to generate stable, multi-user demand, especially in low-density or informal markets. Anchor-business-community models, as evidenced in Ghana, Malawi, and Tanzania, present a promising pathway. These models use an energy-intensive enterprise, often a food processor or mill, to stabilise demand and extend energy services to smaller users or surrounding households. Integrating circular strategies, such as fertiliser production from biogas systems or shared cold storage, as seen in Kenya and Ghana, respectively, enhances economic viability while building community-wide resilience. However, realising such models requires local capacity to manage collective infrastructure, maintain equipment, and coordinate financing. National energy programmes should support the incubation of anchor-based energy enterprises through targeted subsidies, training for local cooperatives, and dedicated legal frameworks to manage co-ownership and revenue sharing.

Non-financial support is not optional, it is foundational

Enterprise-level transitions require more than access to capital or hardware. As repeatedly shown across the case studies, women entrepreneurs face multiple non-

financial constraints: from limited energy literacy and technical training to market access barriers and weak institutional support. These constraints are often invisible to energy planners but profoundly shape the feasibility of productive use transitions (Pueyo, Bawakyillenuo, et al., 2020; Pueyo, Carreras, et al., 2020). Embedding enterprise support within energy programmes, for example, through technical advisory services, vocational training, or linkage to women's business networks, is essential to transform access into sustained productivity. The role of trusted intermediaries or "reference entrepreneurs," as seen in Tanzania, should be formalised in programme design as a lever for social learning and trust building.

Macroeconomic and institutional risks require active mitigation, not passive accommodation

Currency risk, inflation, and regulatory unpredictability are not abstract macroeconomic concerns, they are enterprise-level inhibitors to clean energy investment. In contexts like Nigeria and Tunisia, even relatively well-structured financial instruments falter due to underlying policy volatility or legacy subsidy distortions. Energy finance mechanisms must be accompanied by institutional reforms: clarity in licensing, transparency in tariff setting, and long-term policy commitments are preconditions for investor confidence and enterprise-level adoption. Risk-sharing tools, such as local currency facilities, maintenance guarantees, and long-term service contracts, should be mainstreamed in donor-supported energy access initiatives (Dibaba et al., 2023; Falchetta et al., 2022). Without these instruments, clean energy systems will remain niche or grant-dependent, unable to transition into scalable and sustainable development engines.

Figure 60 summarises the main cross-cutting insights for energy policy, finance, and enterprise support needed to enable inclusive clean energy transitions.

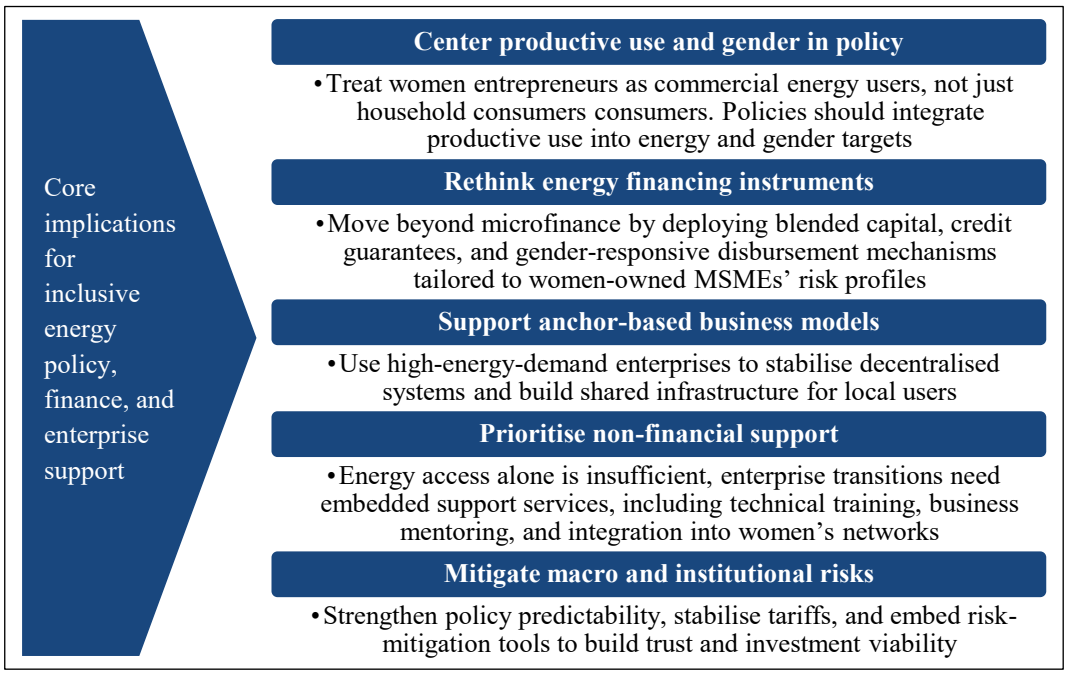

Figure 60. Policy and finance implications for inclusive energy transitions

Taken together, these implications point to a broader agenda for inclusive energy transitions, one that moves beyond supply-side hardware deployment and into the institutional, financial, and policy architectures that shape how energy systems intersect with enterprise ecosystems and gendered realities. As the final section of this research, the outlook chapter explores how these insights can inform future research, policy innovation, and the scaling of equitable energy transitions across Africa and beyond.

9.3 Outlook

The preceding discussion has shown that advancing energy access for women-owned enterprises involves designing and sustaining ecosystems that align infrastructure with institutions, investment with inclusion, and business models with the lived realities of entrepreneurs. The implications for energy policy, finance, and enterprise support are clear, yet translating these insights into transformative change requires more than static recommendations. It calls for a strategic and future-oriented agenda that bridges existing constraints with emerging opportunities for inclusive and sustainable energy transitions.

This final section steps back to reflect on what is still needed, analytically, practically, and institutionally, to ensure that clean energy transitions truly serve as engines of inclusive development.

Despite the richness of the case studies and scenario analyses presented, several gaps remain. First, the business models and financing schemes evaluated in this research, while empirically grounded, are still simulations. They represent theoretically viable pathways, informed by real enterprises and national contexts, but have not yet been tested under actual financial, regulatory, or behavioural conditions. Future work must therefore move from modelled scenarios to pilot implementation, ideally through partnerships that embed research within donor programmes, financial institutions, or national electrification plans. Testing how blended capital performs, how maintenance is managed, or how repayment risk evolves could offer critical feedback to improve both design and policy relevance.

Second, while this study has applied a gender lens, future research should deepen intersectional and comparative perspectives to better capture the complex realities of enterprise-level energy access. The women entrepreneurs featured here represent a range of geographies, sectors, and energy needs, but they are not a homogenous group. Important dimensions such as age, education, marital status, rurality, and informal sector participation likely shape energy access constraints and decision-making power in ways this study could not fully explore. Unpacking these intersecting factors would offer a richer understanding of the structural conditions under which energy transitions succeed or stall. Additionally, a key methodological limitation of this study is the absence of a male-owned control group in the research phases presented in Chapters 6, 7, and 8. While Chapter 5 includes a gender-disaggregated analysis based on the Nigerian survey sample, the in-depth interviews focused solely on women-owned and co-owned enterprises. Incorporating structured comparisons across male-, female-, and jointly owned enterprises using identical instruments would allow future research to more systematically assess how ownership structures shape energy investment behaviour, technology adoption, and long-term performance.

Third, the future of productive energy access lies in recognising that energy does not operate in a vacuum. It is increasingly entangled with other services, such as water, mobility, digital infrastructure, and food systems. Several of the enterprises studied here already demonstrate this convergence, through cooling services, agri-processing integration, or circular use of biowaste. But such linkages are rarely supported through coherent policy or finance frameworks. Research and

programme design must begin to treat energy not just as an endpoint, but as an enabling platform for multi-sectoral development, particularly in rural and peri-urban economies.

Fourth, energy transitions that aim to be equitable must also be held to account. The global discourse on "gender-responsive energy planning" has grown more visible, yet national policy systems still struggle to move from rhetoric to operational practice. Tariff structures often fail to reflect productive use needs; clean cooking programmes ignore thermal energy for enterprise; subsidy schemes rarely reach beyond household use; and mini-grid policies exclude informal and commercial actors by default. There is an urgent need for rigorous policy evaluation and systems change research, not just to count connections or megawatts, but to assess whether national frameworks are truly enabling women-owned enterprises to access and use energy in ways that enhance economic agency and resilience.

This work also raises important reflections about the temporal mismatch between energy infrastructure and the institutional timelines of development assistance. Many promising enterprise-energy models require years to stabilise, mature, and deliver returns. Yet donor project cycles remain short, often focused on immediate installations or discrete outputs. A more strategic investment in ecosystem infrastructure, such as maintenance networks, vocational training, market linkages, and local finance institutions, is essential for a durable impact. These "softer" elements, though harder to measure, are often what determines whether energy systems endure or dissolve.

Finally, the central thesis of this research, that women-owned enterprises are not passive beneficiaries but active agents of energy transition, must be mainstreamed in both academic and practitioner thinking. The question is no longer whether gender matters in energy access, but how to design systems that respond to it meaningfully. This requires embedding women's enterprises not only in impact narratives but in the core of investment strategies, regulatory designs, and infrastructure plans.

The path toward sustainable development will not be paved by energy technologies alone, but by the systems that are built to deliver, finance, and govern them. Ensuring those systems are inclusive of gender, of enterprise diversity, of socio-economic constraints, is not a peripheral task. It is the core challenge of equitable energy transitions. This research hopes to be a stepping stone toward meeting that challenge.

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Appendix A

This appendix provides supplementary comparative data referenced in Chapter 4. It presents a cross-country snapshot of MSMEs in countries with relatively high enterprise density (measured as MSMEs per 1,000 inhabitants) and the share of women-owned MSMEs. The table supports the rationale for country case selection by contextualising both the scale and the gender distribution of the MSME sector.

Appendix A presents the following table:

- Table A.1. Country ranking by highest number of MSMEs per 1,000 inhabitants and share of women-owned MSMEs

Table A.1. Country ranking by highest number of MSMEs per 1,000 inhabitants and share of women-owned MSMEs

Country	Year	Number of MSMEs				MSME/1,000 inhabitants	Share of women-owned MSMEs (%)
		micro	small	medium	total MSMEs		
Nigeria	2013	36,994,578	68,168	4,670	37,067,416	215.7	43.3%
Ghana	2015	1,083,938	802,928	338,372	2,225,238	80.7[1]	31.6%[2]
Tanzania	2012	3,074,736	88,150		3,162,886	64.4	53.9%
Tunisia	2016	720,639	16,115	2,485	739,239	64.1	49.5%[2]
Malawi	2012	799,859[3]	167,872[3]	19,749[3]	987,480	61.3	46.0%
Egypt	2017	3,431,649	421,386	8,311	3,861,346	39.6	17.8%[2]
Kenya	2016	1,438,109	110,938	11,480	1,560,527	31.4	31.4%
Senegal	2016	400,540	4,895	1,632	407,066	25.7	22.9%[2]
Algeria	2017	1,035,891	21,202	3,196	1,060,289	25.7	15%[2]

Morocco	2002	733,662	14,123	2,417	750,202	25.4	13.1%[2]

Notes:

[1] The primary source indicates that the number of MSME per 1,000 people amounts to 19.7 instead of 80.7. However, the value is kept as per the MSME database (SME Finance Forum, 2023).

[2] Since the MSME Economic Indicators Database 2019 does not provide data on the share of women-owned MSME for Algeria, Ghana, Egypt, Morocco, Senegal, and Tunisia, data from the World Bank Group (2023a) were added indicating firms with female participation in ownership in these countries. These data values represent the percentage of firms with a woman among the principal owners. The reference years of the World Bank data for Algeria (2007), Ghana (2013), Egypt (2016), Morocco (2007), Senegal (2014), and Tunisia (2013) do not match the years of the MSME Economic Indicators Database 2019 (SME Finance Forum, 2023) which may compromise data comparability.

[3] Values were taken from the primary source as indicated by the MSME Economic Indicators Database 2019.

Appendix B

This appendix provides supplementary materials and data tables referenced in Chapter 5. It includes the full questionnaire instrument, a comprehensive set of conversion factors, and disaggregated summary statistics that underpin the cross-country and gender-based analysis. Notably, Table B.2, which lists conversion factors for fuel use, production output, and exchange rates, is also partially used in Chapters 6 and 7 to support the interpretation of data from face-to-face interviews.

Appendix B presents the following tables:

- Table B.1. Web-based questionnaire form
- Table B.2. Conversion factors (fuel, production output, and exchange rates)
- Table B.3. Overview of the dataset
- Table B.4a. Number of energy carriers utilised by country, and gender-based enterprise ownership structure
- Table B.4b. Electric and non-electric demand levels for productive use
- Table B.5a. Number of energy carriers utilised by gender-based enterprise ownership structure in Nigeria
- Table B.5b. Electric and non-electric demand levels for productive use in Nigeria

Table B.1. Web-based questionnaire form

Introduction	Thank you for participating in this online survey on energy use in textile and food industries. This survey has a total of two sections and 14 questions, which will take approximately 15 minutes of your time.			Rationale for questions (not visible to research participants)
Section 1	FIRST SECTION: At first, we would like to know more about the enterprise. This section has 10 questions.			
Question	Type of answer choice	Answer choices	Notes (if applicable)	
1.1 Are you the owner of a micro, small or medium-sized enterprise in the textile or food sector?	Multiple choice	"Yes", "No"	n/a	Identification of the respondent and their role in the enterprise
1.2 In which country is the headquarters of the enterprise?	Dropdown (one answer choice possible only)	"Egypt", "Ghana", "Kenya", "Malawi", "Tanzania", "Tunisia"	n/a	Geographical location
1.3 In which city, town, or village is the enterprise located?	Short answer	-	If the enterprise has more than one location, please write down the names of all locations.	Urban/rural setting

1.4 Please indicate the gender of the owner.	Multiple Choice (one answer choice possible only)	"Female", "Male", "Other", "Prefer not to say"	n/a	Ownership structure
1.5 Please indicate the gender of the co-owner (if any).	Multiple Choice (one answer choice possible only)	"Female", "Male", "Other", "Prefer not to say", "No co-owner"	n/a	
1.6 Please write down the number of employees of the enterprise.	Short answer	-	(a) Value doesn't include the owner and co-owner (if any). (b) The value can be equal or above zero.	Enterprise size
1.7 Please indicate whether the enterprise is registered and/or licensed.	Multiple choice (one answer choice possible only)	"Yes", "No", "I prefer not to say", "I don't know"	n/a	Formal/legal enterprise status
1.8 Please select the sector that describes the enterprise best.	Dropdown (one answer choice possible only)	Selected ISIC activities under ISIC Divisions 01, 02, 03, 10, 11, 12, 13, 14, 15, 16, 31, 32, and 56 which relate to the food and textile sector	n/a	Business sector identification

1.9 Please describe in your own words the activities of the enterprise.	Paragraph	-	(a) Activities in the textile sector could be for example: production of textiles/garments/hides & skins, i.e., preparing raw material, spinning, knitting, weaving, dyeing, printing, finishing, sewing, etc. (b) Activities in the food sector could be for example: wheat/maize milling, drying fish/vegetables, milk production/storage, livestock breeding, etc.	Cross-checking of exact business activity
1.10 Please write down the annual production output of the enterprise.	Paragraph	-	(a) Please indicate value, unit, and produced item. The response could be for example: 800 kg tomato purée/year, or 1,000 litres olive oil/year, or 1,500 leather shoes/year. (b) Please list all production outputs.	Production output (in combination with question 2.4)
Section 2	SECOND SECTION: We would now like to understand the extent to which energy is used in the enterprise. This last section has 4 questions.			

Question	Type of answer choice	Answer choices	Notes (if applicable)	Rationale for questions (not visible to research participants)
2.1 Please select the source of energy that is used in the enterprise for its energetic and electric needs.	Checkboxes (multiple answers choices possible)	"Electricity from the national grid", "Diesel", "Gasoline", "Kerosene", "Solar energy", "Biomass", "LPG", "Natural gas", "Other", "None", "I don't know"	(a) It is possible to select more than one energy source.	Energy carrier use
2.2 Please select the average monthly electricity consumption level that reflects best the electric needs of the enterprise.	Dropdown (one answer choice possible only)	[Consumption brackets from 0-20 kWh until 181-200 kWh in 20 kWh ranges respectively], "Above 200 kWh", "None", "I don't know"	(a) Only select from options, if applicable. Otherwise, select "none". (b) If you don't know the electricity consumption (given in kWh), you can estimate it by multiplying the wattage of a device with the hours per month the device is working, e.g. a light bulb of 100 W working for 30 hours per month consumes: 100W x 30 h = 3,000 Wh = 3 kWh.	Consumption level

2.3 Please indicate the average monthly fuel consumption that reflects best the energy needs of the enterprise.	Short answer	-	(a) If not applicable, write "none". (b) Please indicate value, unit, and energy source. The response could be for example: 20 litres diesel/month, or 30 kg LPG/month, etc. (c) If you do not know the answer, write "I don't know".	
2.4 Please write down the yearly average energy costs (electricity and fuel) of the enterprise.	Short answer	-	Notes: (a) Please insert the average cost of 2022 and indicate the value in local currency. (b) If you do not know the answer, write "I don't know".	Energy expenditure (in combination with question 1.10)

Table B.2. Conversion factors (fuel, production output, and exchange rates)

Fuel conversion factors to kilowatt-hour				
Fuel type	**Net calorific value or lower heating value (MJ/kg)**	**Fuel density (kg/L)**	**Assumed equipment efficiency (%)**	**References**
Petrol	44.3	0.79	$30\%_{e}$	(Garg et al., 2006; Statistic Netherlands, 2025); Stiel & Skyllas-Kazacos, 2012)
Diesel	43.0	0.84	$30\%_{e}$	(Garg et al., 2006; Statistics Netherlands, 2025; Stiel & Skyllas-Kazacos, 2012)
LPG	47.3	0.53	$57\%_{th}$	(Garg et al., 2006; Shen et al., 2018; Statistics Netherlands, 2025)
Natural gas	48.0	-	$60\%_{th}$	(Garg et al., 2006; Islam et al., 2022; Statistics Netherlands, 2025)
Briquettes	15.6	-	$60\%_{th}$	(Garg et al., 2006; Kanase et al., 2021; Statistics

				Netherlands, 2025)
Charcoal	29.5	-	22%$_{th}$	(Ekouedjen et al., 2020; Garg et al., 2006; Statistics Netherlands, 2025)
Firewood	15.6	-	22%$_{th}$	(Ballard-Tremeer & Jawurek, 1996; Garg et al., 2006; Statistics Netherlands, 2025)

Production output conversion factors

Type of production output	**Weight of production output**	**References**
Garments and clothes	0.047 kg/piece	(Tash, 2015)
Accessories	0.016 kg/piece	(Tash, 2015)
A pair of shoes	1 kg/pair	Author's assumption
Baked goods	0.25 kg/piece	Author's assumption
Cow	450.83 kg/cow	(Kubkomawa, 2017)
Goat	31.25 kg/goat	(Njoro, 2003)

Chicken	1 kg/chicken	Author's assumption
Dried fish	0.1 kg/piece	(Olayemi et al., 2011)
Prepared meal	0.5 kg/meal	Author's assumption
Packet of maize	1 kg/packet	Author's assumption
Tray of eggs	0.323 kg/trey	(Nepomuceno et al., 2014)

Average exchange rates for the year 2022

Local currency	Exchange rate to USD	Reference
Egyptian pound (EGP)	19.15	(Central Bank of Egypt, 2023)
Ghanaian cedi (GHC)	8.45	(Central Bank of Ghana, 2023a)
Kenyan shilling (KES)	117.83	(Central Bank of Kenya, 2023a)
Malawian kwacha (MWK)	1,023.80	(Xe, 2023a)
Nigerian naira (NGN)	422.45	(Central Bank of Nigeria, 2023)
Tanzanian shilling (TSh)	2332.24	(Xe, 2023b)
Tunisian dinar (TND)	3.11	(Central Bank of Tunisia, 2023)

Abbreviations: % = percent; e = conversion efficiency to electric energy as end-use form; kg = kilogramme; L = litre; MJ = Megajoule; th = conversion efficiency to thermal energy as end-use form; USD = United States dollar

Table B.3. Overview of the dataset

Country	Respondents		Industry sector				Gender-based ownership structure						Enterprise size			
			Food		Textile		Sole female		Female-female		Gender-diverse		Micro		Small	
	#	%	#	%	#	%	#	%	#	%	#	%	#	%	#	%
Egypt	4	6.15	2	3.92	2	14.92	4	20.00	0	0.00	0	0.00	3	7.00	1	4.00
Ghana	3	4.62	1	1.96	2	14.92	2	10.00	1	5.00	0	0.00	1	2.00	2	9.00
Kenya	12	18.46	12	23.53	0	0.00	4	20.00	3	15.00	5	20.00	8	19.00	4	17.00
Malawi	10	15.38	6	11.76	4	28.57	2	10.00	6	30.00	2	8.00	6	14.00	4	17.00
Nigeria	26	40.00	23	45.10	3	21.43	5	25.00	6	30.00	15	60.00	19	45.00	7	30.00
Tanzania	3	4.62	0	0.00	3	21.43	0	0.00	2	10.00	1	4.00	0	0.00	3	13.00
Tunisia	7	10.77	7	13.73	0	0.00	3	15.00	2	10.00	2	8.00	5	12.00	2	9.00
Total	**65**	**100**	**51**	**78.46**	**14**	**21.54**	**20**	**30.77**	**20**	**30.77**	**25**	**38.46**	**42**	**64.62**	**23**	**35.38**

Table B.4a. Number of energy carriers utilised by country, and gender-based enterprise ownership structure

Country	**Gender-based enterprise ownership structure**								
	Sole female			**Female-female**			**Gender-diverse**		
Number of energy carriers	**1**	**2**	**≥3**	**1**	**2**	**≥3**	**1**	**2**	**≥3**
Percent	%	%	%	%	%	%	%	%	%
Egypt	25.00	22.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ghana	0.00	11.11	33.33	0.00	0.00	33.33	0.00	0.00	0.00
Kenya	25.00	11.11	33.33	0.00	22.22	33.33	14.29	20.00	25.00
Malawi	12.50	11.11	0.00	50.00	22.22	0.00	14.29	0.00	12.50
Nigeria	25.00	22.22	33.33	25.00	33.33	33.33	28.57	80.00	62.50
Tanzania	0.00	0.00	0.00	25.00	0.00	0.00	14.29	0.00	0.00
Tunisia	12.50	22.22	0.00	0.00	22.22	0.00	28.57	0.00	0.00
Share within the respective	**40.00**	**45.00**	**15.00**	**40.00**	**45.00**	**15.00**	**28.00**	**40.00**	**32.00**

gender-based ownership structure									
Share within the total sample	**12.31**	**13.85**	**4.62**	**12.31**	**13.85**	**4.62**	**10.77**	**15.38**	**12.31**

Table B.4b. Electric and non-electric demand levels for productive use

	Monthly electric demand in kWh/month														
Country	**Sole female**					**Female-female**					**Gender-diverse**				
	None	Don't know	1-100	101-200	Above 200	None	Don't know	1-100	101-200	Above 200	None	Don't know	1-100	101-200	Above 200
	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
Egypt	0.00	40.00	0.00	28.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ghana	0.00	20.00	25.00	0.00	0.00	0.00	33.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Kenya	0.00	20.00	25.00	0.00	66.67	0.00	0.00	28.57	0.00	25.00	0.00	0.00	20.00	25.00	33.33
Malawi	0.00	0.00	25.00	0.00	33.33	0.00	66.67	42.86	25.00	0.00	50.00	0.00	0.00	25.00	0.00
Nigeria	100.00	0.00	25.00	42.86	0.00	100.00	0.00	14.285	25.00	50.00	0.00	0.00	60.00	50.00	66.67
Tanzania	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	25.00	25.00	0.00	100.00	0.00	0.00	0.00
Tunisia	0.00	20.00	0.00	28.57	0.00	0.00	0.00	14.285	25.00	0.00	50.00	0.00	20.00	0.00	0.00
Share within the respective	**5.00**	**25.00**	**20.00**	**35.00**	**15.00**	**10.00**	**15.00**	**35.00**	**20.00**	**20.00**	**8.00**	**4.00**	**20.00**	**16.00**	**52.00**

gender-based ownership structure															
Share within the total sample	**1.54**	**7.69**	**6.15**	**10.77**	**4.62**	**3.08**	**4.62**	**10.77**	**6.15**	**6.15**	**3.08**	**1.54**	**7.69**	**6.15**	**20.00**

	Monthly non-electric demand in kWh/month														
Country	**Sole female**					**Female-female**					**Gender-diverse**				
	None	Don't know	1-400	401-800	Above 800	None	Don't know	1-400	401-800	Above 800	None	Don't know	1-400	401-800	Above 800
	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
Egypt	20.00	25.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ghana	0.00	25.00	0.00	0.00	0.00	0.00	33.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Kenya	20.00	0.00	50.00	100.00	100.00	0.00	0.00	50.00	0.00	0.00	13.33	14.285	0.00	100.00	100.00
Malawi	20.00	0.00	0.00	0.00	0.00	54.55	0.00	0.00	0.00	0.00	0.00	28.57	0.00	0.00	0.00
Nigeria	30.00	25.00	50.00	0.00	0.00	27.27	33.33	33.33	0.00	0.00	73.33	42.86	100.00	0.00	0.00

Tanzania	0.00	0.00	0.00	0.00	0.00	18.18	0.00	0.00	0.00	0.00	6.67	0.00	0.00	0.00	0.00
Tunisia	10.0	25.00	0.00	0.00	0.00	0.00	33.33	16.67	0.00	0.00	6.67	14.285	0.00	0.00	0.00
Share within the respective gender-based ownership structure	**50.00**	**40.00**	**5.00**	**5.00**	**5.00**	**55.00**	**15.00**	**30.00**	**0.00**	**0.00**	**60.00**	**28.00**	**4.00**	**4.00**	**4.00**
Share within the total sample	**15.38**	**12.31**	**3.08**	**1.54**	**1.54**	**16.92**	**4.62**	**9.23**	**0.00**	**0.00**	**23.08**	**10.77**	**1.54**	**1.54**	**1.54**

Table B.5a. Number of energy carriers utilised by gender-based enterprise ownership structure in Nigeria

	Gender-based enterprise ownership structure														
	Sole female			**Female-Female**			**Gender-diverse**			**Sole male**			**Male-male**		
Number of energy carriers	**1**	**2**	**≥3**	**1**	**2**	**≥3**	**1**	**2**	**≥3**	**1**	**2**	**≥3**	**1**	**2**	**≥3**
Percent	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
Share within the respective gender-based ownership structure	40.00	40.00	20.00	33.33	50.00	16.67	13.33	53.33	33.33	30.77	38.46	30.77	28.57	42.86	28.57
Share within the total sample	4.35	4.35	2.17	4.35	6.52	2.17	4.35	17.39	10.87	8.70	10.87	8.70	4.35	6.52	4.35

Table B.5b. Electric and non-electric demand levels for productive use in Nigeria

Monthly electric demand					
Monthly demand in kWh/month	**Sole female**	**Female-female**	**Gender-diverse**	**Sole male**	**Male-male**
Percent	%	%	%	%	%
None	20.00	33.33	0.00	0.00	0.00
Don’t know	0.00	0.00	0.00	0.00	0.00
1-100	20.00	16.67	20.00	15.38	0.00
101-200	60.00	16.67	13.33	46.15	14.29
Above 200	0.00	33.33	66.67	38.46	85.71
Monthly non-electric demand					
Monthly demand in kWh/month	**Sole female**	**Female-female**	**Gender-diverse**	**Sole male**	**Male-male**
Percent	%	%	%	%	%
None	60.00	50.00	73.33	53.85	57.14

Don’t know	40.00	16.67	20.00	15.38	28.57
1-100	0.00	33.33	6.67	7.69	0.00
101-200	0.00	0.00	0.00	0.00	14.29
Above 200	0.00	0.00	0.00	23.08	0.00

Appendix C

This appendix provides supplementary materials and detailed empirical data referenced in Chapter 6, which presents the second phase of data collection based on energy audits conducted through face-to-face interviews. The appendix includes the full interview questionnaire, context-specific tariff data, and qualitative coding structure used to analyse responses. It also contains detailed sample characteristics and energy access performance ratings based on the World Bank's MTF.

Appendix C presents the following tables:

- Table C.1. Full interview questionnaire
- Table C.2. Grid electricity tariffs inclusive of taxes, levies, and other charges
- Table C.3. Full description of the thematic categories for qualitative analysis
- Table C.4. Sample overview and enterprise characteristics
- Table C.5. Energy access performance using the World Bank's MTF

Table C.1. Full interview questionnaire

Introduction	• Provide the research background • Outline the content and objective of the interview • Explain the data collection, analysis, and publication process • Obtain informed verbal consent			
Thematic area	**#**	**Data of interest**	**Question(s) posed**	**Answer choice**
Socio-economic characteristics	1	Location	What is the name of the city or village where your business is located?	Short answer
	2	Demographics of the entrepreneur	If you are comfortable sharing this information, could you specify your age and gender?	Short answer
	3	Educational background of the entrepreneur	What is the highest level of education that you achieved? Did you obtain any additional certifications in the past? If yes, what kind of certificates?	Short answer
	4	Financial responsibilities of the entrepreneur, besides the business	Do you have any dependents? If yes, how many?	Short answer
	5	The underlying motivation of the entrepreneur	What was the reason for you to start this enterprise?	Long answer possible

6	Gender-based ownership structure	Are you the sole owner of the enterprise? How many co-owners do you have? What is/are the genders of the co-owner(s)?	Short answer
7	Enterprise size	How many full-time employees do you have? What is/are the gender(s) of your full-time employee(s)?	Short answer
8	Industry sector	What industry sector do you belong to?	Food or textile
9	Business activity	How would you describe your business activities?	Long answer possible
10	Enterprise status	Is your enterprise registered?	Yes/no
11	Year of establishment or business start	What year did you register your enterprise? When did you start your enterprise?	Short answer
12	Production output	What type of goods do you produce? Can you provide the amount of each production good produced (the unit is given per the interviewee's preference)?	Short answer

	13	Profit margin	If you are comfortable sharing this information, could you provide your profit margin, considering total revenue and total costs?	Short answer
	14	Business challenges related to gender	As a female entrepreneur do you feel you encounter distinct challenges specifically related to your gender?	Long answer possible
Energy access and use	1	Energy carrier use	Can you name each activity that requires a form of energy? What kind of energy do you use?	Long answer possible
	2	Temperature requirements	Is heat needed in your production process? If yes, what temperature requirements do you have for each activity?	Short answer
	3	Energy consumption	What is your monthly energy consumption (the unit is given per the interviewee's preference)?	Short answer

	4	Energy expenditure	Could you specify the amount you pay for each type of energy source you use (the unit is given per the interviewee's preference)? Could you estimate the percentage of your total expenditure spent on energy costs? Could you estimate the percentage of your total revenue allocated to energy costs?	Short answer
	5	Energy supply reliability	Do you experience blackouts or fuel shortages? If yes, how often and for how long (the unit is given per the interviewee's preference)?	Short answer
	6	Appliance use	Can I have a look at the appliances that are used and note down the Wattage? For how many hours per day do you use each appliance? At what time of the day do you usually use each appliance?	Long answer possible
Potential for renewable energy adoption	1	Process waste	Do you generate any process waste? If yes, what kind of waste and in what quantities (the unit is given per the interviewee's preference)?	Short answer
	2	Starting capital and investments	If you feel comfortable sharing this information, could you specify the types of assets you own for your business? What is	Short answer

			the amount you paid for them? What are the methods you used to finance these investments?	
	3	Enterprise-related challenges	What are your main challenges running an enterprise?	Long answer possible
	4	Barriers to renewable energy adoption	What factors do you perceive as preventing you from adopting renewable energy technologies in your business operations?	Long answer possible
	5	Drivers for renewable energy adoption	What motivates you to adopt renewable energy solutions?	Long answer possible
	6	Willingness to invest in or pay for new technologies/services	Are you willing to invest in or pay for renewable energy solutions/services for your business? If yes, could you specify the amount you will invest/pay? What would be your preferred method of payment?	Short answer
Concluding remarks	• Thank the participant for their time and for sharing the given information • Ask the participant if they would like to share any additional information or if they have any questions			

Table C.2. Grid electricity tariffs inclusive of taxes, levies, and other charges

Country	Consumption bracket (either kWh/month or other type of use)	Grid tariff for commercial or industrial end-users (USD¢/kWh)		Currency conversion factor to USD	Tariff validity since
		specific tariff	average tariff		
Egypt			4.59	27.87	July 2022
(EgyptERA, 2022)	0-100	2.33			
	0-250	4.42			
	0-600	5.02			
	601-1,000	5.56			
	above 1,000	5.74			
Ghana			15.62	11.02	January 2023
(PURC, 2023)	0-300	13.57			
	301-600	13.43			
	above 600	19.85			
Kenya			15.26	139.35	April 2023
(EPRA, 2023; KPLC, 2023)	31-100	17.80			
	above 100	17.68			
	TOU above 100	10.69			
Malawi			15.29	1017.82	March 2021
(ESCOM, 2021)	Prepaid single phase	13.43			

	Postpaid single-phase	18.20			
	Prepaid three-phase	14.85			
	Postpaid three-phase	14.71			
Nigeria				1615.25	September 2024
(NERC, 2024)	**Kaduna DisCo**		5.51		
	Average A (min. 20h/day)	13.94			
	Average B (min. 16h/day)	4.39			
	Average C (min. 12h/day)	3.54			
	Average D (min. 8h/day)	2.84			
	Average E (min. 4h/day)	2.84			
	Ikeja DisCo		5.40		
	Average A (min. 20h/day)	13.94			
	Average B (min. 16h/day)	4.34			
	Average C (min. 12h/day)	3.31			
	Average D (min. 8h/day)	2.67			
	Average E (min. 4h/day)	2.67			

	Eco DisCo		5.36		
	Average A (min. 20h/day)	13.94			
	Average B (min. 16h/day)	4.20			
	Average C (min. 12h/day)	3.39			
	Average D (min. 8h/day)	2.64			
	Average E (min. 4h/day)	2.64			
	Ibadan DisCo		5.22		
	Average A (min. 20h/day)	13.94			
	Average B (min. 16h/day)	4.58			
	Average C (min. 12h/day)	3.67			
	Average D (min. 8h/day)	2.94			
	Average E (min. 4h/day)	2.94			
Tanzania			14.75	2415.05	July 2022
(EWURA, 2021)	75-7,500	14.75			
Tunisia			9.31	3.29	May 2022
(STEG, 2022)	0-100	3.91			
	101-200	7.24			

201-300	8.86
301-500	12.23
above 501	14.33

Table C.3. Full description of the thematic categories for qualitative analysis

Themes	Description
Business challenges related to the gender of the women entrepreneur	
None	No challenge was identified by the entrepreneur
Gender-biased attitudes	Discriminatory attitudes and biases encountered by women in the business sphere, hindering their opportunities for growth and success
Gender roles and norms	societal expectations and behaviours associated with men and women, often constraining women
Limited access to resources	Restrictions in accessing productive resources, such as access to finance or land ownership, due to gender or other intersecting factors like tribe or region of origin
Lack of technical know-how	Limited access to technical skills and knowledge necessary for business operations
Sexual harassment	Instances of sexual misconduct or abuse, whether verbal or physical, exacerbate challenges for female entrepreneurs, creating hostile work environments
Work-life balance	Striking a balance between work and personal life is challenging due to societal expectations and traditional gender roles, which impact women entrepreneurs

Restricted mobility	Limitations on women's freedom of movement, whether due to safety concerns or cultural norms, hinder their ability to conduct business activities effectively
	Barriers to renewable energy adoption
Lacking knowledge	Unawareness of renewable energy technologies and their benefits inhibits entrepreneurs from exploring and implementing sustainable energy solutions
Lacking available technologies	The perceived lack of suitable technologies and compatible equipment tailored to business needs within the respective country represents a significant barrier to renewable energy adoption
Lacking access to finance	Financial accessibility constraints for renewable energy investments impede entrepreneurs from making upfront investments in sustainable energy solutions
Lacking facility	Some entrepreneurs face challenges obtaining a facility (space) or approval from landlords, which are necessary prerequisites for installing renewable energy infrastructure
Regulatory and policy hurdles	Refers to perceived complex permitting processes or ambiguous regulations, creating uncertainty and delay in renewable energy adoption efforts
	Drivers for renewable energy adoption
None	No driver was identified by the entrepreneur
Economic savings	Financial benefits stemming from reduced energy costs and long-term cost savings

Price stability	The desire for cost consistency and the potential for reducing operational expenses from fuel and grid use contribute to the appeal of renewable energy technologies
Environment and sustainability	Viewing renewable energy adoption to reduce carbon footprints and promote eco-friendly practices, thereby enhancing corporate social responsibility (CSR)
Available facility	An existing facility that is available to the entrepreneur and supports renewable energy integration
Unreliable energy access	Regular grid blackouts or unreliable fuel carriers that harm business performance incentivise entrepreneurs to explore the use of alternative energy sources for increased energy supply
Increased safety	Ensuring a safer work and living environment by adopting renewable energy technologies to reduce risks associated with handling, storing, or transporting generator fuel, such as fire hazards or accidental spills.
Reduced inconveniences	The desire to adopt renewable energy technologies to minimise noise pollution from traditional generators for a quieter and more comfortable environment, while also reducing the hassle and stress of securing a consistent fuel supply, thereby enhancing convenience and well-being.

Table C.4. Sample overview and enterprise characteristics

ISIC	Country	Gender in ownership	Access type	Enterprise				
				Type	Formality	Year	Size	Location
01	Tunisia	Sole female	On-grid	For-profit	Registered	2017	Micro	Home
10	Ghana	Sole female	On-grid	For-profit	Registered	2020	Micro	Facility
10	Ghana	Gender-diverse	On-grid	Not-for-profit	Registered	2016	Micro	Facility
10	Ghana	Sole female	On-grid	For-profit	Registered	2021	Micro	Home
10	Ghana	Sole female	On-grid	For-profit	Registered	2021	Micro	Home
10	Kenya	Gender-diverse	On-grid	For-profit	Registered	2018	Small	Facility
10	Kenya	Sole female	On-grid	For-profit	Registered	2021	Micro	Both
10	Malawi	Gender-diverse	On-grid	Not-for-profit	Registered	2005	Micro	Home
10	Malawi	Sole female	On-grid	For-profit	Registered	2010	Small	Home
10	Malawi	Sole female	On-grid	For-profit	Not registered	2021	Micro	Home
10	Malawi	Gender-diverse	Off-grid	For-profit	Not registered	2019	Micro	Facility

10	Nigeria	Gender-diverse	On-grid	For-profit	Registered	2019	Small	Facility
10	Nigeria	Gender-diverse	On-grid	For-profit	Registered	2017	Micro	Facility
10	Nigeria	Sole female	On-grid	For-profit	Registered	2018	Micro	Facility
10	Nigeria	Gender-diverse	Off-grid	For-profit	Registered	2023	Micro	Facility
10	Nigeria	Sole female	On-grid	For-profit	Not registered	2021	Micro	Facility
10	Nigeria	Gender-diverse	On-grid	For-profit	Registered	2017	Micro	Both
10	Nigeria	Gender-diverse	On-grid	For-profit	Registered	2020	Micro	Facility
10	Tunisia	Sole female	On-grid	For-profit	Registered	2018	Micro	Facility
13	Egypt	Sole female	On-grid	For-profit	Registered	2019	Small	Facility
13	Nigeria	Sole female	On-grid	For-profit	Registered	2020	Micro	Home
13	Tanzania	Gender-diverse	On-grid	Not-for-profit	Registered	2020	Micro	Facility
14	Ghana	Sole female	On-grid	Not-for-profit	Registered	2017	Micro	Home
14	Kenya	Sole female	On-grid	For-profit	Registered	2015	Micro	Facility

14	Kenya	Female-female	On-grid	Not-for-profit	Registered	2020	Small	Facility
14	Malawi	Gender-diverse	On-grid	For-profit	Registered	2022	Micro	Facility
14	Malawi	Sole female	On-grid	For-profit	Registered	2009	Micro	Home
14	Nigeria	Sole female	On-grid	For-profit	Registered	2013	Micro	Facility
14	Nigeria	Gender-diverse	On-grid	For-profit	Registered	2009	Small	Facility
14	Nigeria	Gender-diverse	On-grid	For-profit	Registered	2016	Small	Facility
14	Tanzania	Gender-diverse	On-grid	For-profit	Registered	2012	Small	Home
14	Tanzania	Sole female	On-grid	For-profit	Registered	2010	Micro	Facility
14	Tanzania	Sole female	On-grid	For-profit	Registered	2016	Small	Home
14	Tunisia	Gender-diverse	On-grid	For-profit	Registered	2018	Small	Facility
14	Tunisia	Sole female	On-grid	For-profit	Registered	2016	Small	Facility
15	Nigeria	Sole female	On-grid	For-profit	Registered	2017	Small	Facility
21	Tanzania	Sole female	On-grid	For-profit	Registered	2020	Small	Both

56	Nigeria	Gender-diverse	On-grid	For-profit	Registered	2023	Small	Facility
56	Tanzania	Gender-diverse	On-grid	For-profit	Registered	2019	Small	Home
56	Tanzania	Sole female	On-grid	For-profit	Not registered	2020	Micro	Home

Table C.5. Energy access performance using the World Bank's MTF

ISIC	Country energy carrier	Capacity	Availability	Reliability	Affordability	Legality	Convenience	Health	Safety	Total
01	**Tunisia**									
	electric	5	5	5	0-3	4-5	0-3	4-5	5	**3**
	non-electric	4	2	5	4	4-5	4	2-3	5	**2**
10	**Ghana**									
	electric	5	3	0-3	4	4-5	5	4-5	5	**3**
	non-electric	5	5	5	4	4-5	5	4-5	5	**4**
10	**Ghana**									
	electric	4	2	0-3	4	4-5	5	4-5	5	**2**
	non-electric	4	4	5	4	0-3	4	0-1	4	**1**
10	**Ghana**									

	electric	5	4	4	4	4-5	5	4-5	5	**4**
	non-electric	-	-	-	-	-	-	-	-	**-**
10	**Ghana**									
	electric	5	5	5	4	4-5	5	4-5	5	**4**
	non-electric	5	5	5	4	4-5	5	4-5	5	**4**
10	**Kenya**									
	electric	5	4	0-3	4	4-5	5	4-5	5	**3**
	non-electric	5	5	5	5	4-5	5	2-3	5	**3**
10	**Kenya**									
	electric	5	1	0-3	0-3	4-5	0-3	4-5	5	**1**
	non-electric	5	5	5	4	4-5	0-3	4-5	5	**3**
10	**Malawi**									

	electric	4	4	0-3	4	4-5	5	4-5	5	**3**
	non-electric	5	5	5	4	0-3	4	2-3	5	**3**
10	**Malawi**									
	electric	4	3	0-3	4	4-5	5	4-5	5	**3**
	non-electric	5	0-2	5	0-3	4-5	4	0-1	5	**1**
10	**Malawi**									
	electric	5	2	4	4	4-5	5	4-5	5	**2**
	non-electric	-	-	-	-	-	-	-	-	**-**
10	**Malawi**									
	electric	-	-	-	-	-	-	-	-	**-**
	non-electric	5	4	4	0-3	4-5	4	2-3	5	**3**
10	**Nigeria**									

	electric	5	4	4	4	4-5	4	4-5	5	**4**
	non-electric	5	5	5	0-3	4-5	4	2-3	5	**3**
10	**Nigeria**									
	electric	-	-	-	-	-	-	-	-	-
	non-electric	5	5	5	0-3	4-5	4	2-3	5	**3**
10	**Nigeria**									
	electric	5	1	0-3	5	4-5	4	4-5	5	**1**
	non-electric	5	5	5	0-3	4-5	5	4-5	5	**3**
10	**Nigeria**									
	electric	-	-	-	-	-	-	-	-	-
	non-electric	5	5	5	0-3	4-5	4	2-3	5	**3**
10	**Nigeria**									
	electric	5	3	0-3	5	4-5	4	4-5	5	**3**

	non-electric	5	5	5	0-3	4-5	4	4-5	5	**3**
10	**Nigeria**									
	electric	5	4	0-3	5	4-5	4	4-5	5	**3**
	non-electric	-	-	-	-	-	-	-	-	**-**
10	**Nigeria**									
	electric	5	4	0-3	5	4-5	4	4-5	5	**3**
	non-electric	-	-	-	-	-	-	-	-	**-**
10	**Tunisia**									
	electric	5	5	5	4	4-5	5	4-5	5	**4**
	non-electric	-	-	-	-	-	-	-	-	**-**
13	**Egypt**									
	electric	5	5	5	5	4-5	5	4-5	5	**5**
	non-electric	5	5	5	4	4-5	5	4-5	5	**4**

13	**Nigeria**									
	electric	5	4	4	5	4-5	5	4-5	5	**4**
	non-electric	5	5	5	5	4-5	4	2-3	5	**3**
13	**Tanzania**									
	electric	5	4	4	5	4-5	5	4-5	5	**4**
	non-electric	5	5	5	4	4-5	5	4-5	5	**4**
14	**Ghana**									
	electric	5	4	4	5	4-5	5	4-5	5	**4**
	non-electric	5	5	5	0-3	4-5	5	4-5	5	**3**
14	**Kenya**									
	electric	5	5	5	4	4-5	5	4-5	5	**4**
	non-electric	5	5	5	5	0-3	5	0-1	5	**1**
14	**Kenya**									

	electric	5	5	5	4	4-5	5	4-5	5	**4**
	non-electric	-	-	-	-	-	-	-	-	**-**
14	**Malawi**									
	electric	5	5	5	4	4-5	5	4-5	5	**4**
	non-electric	-	-	-	-	-	-	-	-	**-**
14	**Malawi**									
	electric	5	4	4	4	4-5	5	4-5	5	**4**
	non-electric	-	-	-	-	-	-	-	-	**-**
14	**Nigeria**									
	electric	5	3	4	5	4-5	4	4-5	5	**3**
	non-electric	-	-	-	-	-	-	-	-	**-**
14	**Nigeria**									
	electric	5	5	5	5	4-5	4	4-5	4	**4**

	non-electric	-	-	-	-	-	-	-	-	-
14	**Nigeria**									
	electric	5	3	0-3	5	4-5	4	4-5	5	**3**
	non-electric	-	-	-	-	-	-	-	-	-
14	**Tanzania**									
	electric	5	5	5	4	4-5	4	4-5	5	**4**
	non-electric	-	-	-	-	-	-	-	-	-
14	**Tanzania**									
	electric	5	4	4	5	4-5	5	4-5	5	**4**
	non-electric	-	-	-	-	-	-	-	-	-
14	**Tanzania**									
	electric	5	4	4	5	4-5	4	4-5	5	**4**
	non-electric	-	-	-	-	-	-	-	-	-

14	**Tunisia**									
	electric	5	5	4	4	4-5	5	4-5	5	**4**
	non-electric	-	-	-	-	-	-	-	-	**-**
14	**Tunisia**									
	electric	5	5	5	4	4-5	5	4-5	5	**4**
	non-electric	-	-	-	-	-	-	-	-	**-**
15	**Nigeria**									
	electric	5	3	0-3	5	4-5	0-3	4-5	5	**3**
	non-electric	5	5	5	4	4-5	5	4-5	5	**4**
21	**Tanzania**									
	electric	4	4	4	5	4-5	5	4-5	5	**4**
	non-electric	4	4	4	5	4-5	5	4-5	5	**4**
56	**Nigeria**									

	electric	5	4	4	5	4-5	4	4-5	5	**4**
	non-electric	5	5	5	5	4-5	4	4-5	5	**4**
56	**Tanzania**									
	electric	5	5	4	5	4-5	5	4-5	5	**4**
	non-electric	5	5	5	4	4-5	5	4-5	5	**4**
56	**Tanzania**									
	electric	5	1	0-3	5	4-5	5	4-5	5	**1**
	non-electric	5	5	5	4	4-5	5	4-5	5	**4**

Appendix D

This appendix provides supplementary data and modelling assumptions referenced in Chapter 7. It includes a general summary table of data inputs by country, appliance type, and energy carrier, followed by detailed assumptions and parameters used in selected case study scenarios. These tables support the transparency and reproducibility of the comparative modelling framework used in the chapter.

Appendix D presents the following tables:

Table D.1. Summary of techno-economic inputs by country, type of appliance and energy carrier

Table D.2a. Case Study 1: Techno-economic assumptions and parameters of the base case

Table D.2b. Case Study 1: Techno-economic assumptions and parameters of Scenario 1

Table D.3. Case Study 3: Techno-economic assumptions and parameters of the base case

Table D.4. Case Study 5: Techno-economic assumptions and parameters of the base case

Table D.5a. Case Study 6: Assumptions and parameters for Scenario 2

Table D.5b. Case Study 6: Assumptions and parameters for Scenario 3

Table D.1. Summary of techno-economic inputs by country, type of appliance and energy carrier

	Generator	**Gasifier**	**Boiler**	**Stove; Bunsen burner; kiln**	**Solar PV system**	**Solar PV inverter**	**Battery (lead-acid; lithium-ion)**
Energy carrier	Diesel; Biomethane; Biogas; Syngas	Maize residues	Briquettes; Biogas	Charcoal; Firewood; LPG; Biomass; Biogas; Coconut husks	Solar PV	-	-
Lifetime	20,000[a]	25[b]	20[b]	10[b]	25[b]	15[b]	5[b]; 10[b]
CAPEX and replacement costs (USD/kW$_p$, USD/kW, USD/kWh, USD/unit)							
Ghana	-	-	-	41[c]; 67[c]; 74[c]; 75[c];	1,596[d]	240[e]	143[f]; 455[f]
Kenya	-	-	3,070[e]	-	2,634[d]	240[e]	142[f]; 455[f]
Malawi	600[e]; 568[e]	3,744[e]	-	-	2,211[d]	345[e]	153[f]; 491[f]
Nigeria	600[e]	-	-	25[c]	1,507[d]	240[e]	180[f]; 331[f]

Tanzania	600[e]	-	-	15[c]; 66[c]	-	-	-
Tunisia	600[e]	-	-	-	1,144[d]	240[e]	153[f]; 455[f]
O&M (USD/kW/operating hour, USD/kW/year, USD/kW$_p$/year, USD/kWh/year)							
Ghana	-	-	-	-	10[g]	-	10[h]
Kenya	0.03[i]	-	138	-	10[g]	-	10[h]
Malawi	0.03[i]; 0.04[i]	186[j]	-	-	10[g]	-	10[h]
Nigeria	0.03[i]	-	-	-	10[g]	-	10[h]
Tanzania	0.03[i]	-	-	-	-	-	-
Tunisia	0.02[i]	-	-	-	10[g]	-	10[h]
Energy carrier unit costs							
	Grid electricity	Diesel	Petrol	LPG	Charcoal	Firewood	Sustainable biomass

Ghana	13.57[k]	-	-	0.88[l]	0.35[m]	0.09[m]	Coconut husks: 0.1[m]
Kenya	17.68[k]	1.20[l]	-	-	-	-	Briquettes: 0.011[m]
Malawi	14.85[k]	1.26[l]	-	-	-	-	Maize residues: 0.055[m]
Nigeria	13.94[k]	0.74[l]	0.69[l]	0.61[l]	-	-	-
Tanzania	14.75[k]	1.24[l]	-	0.82[l]	0.62[m]	0.077[m]	-
Tunisia	14.33[k]	0.76[l]	-	-	-	-	-
Nominal discount rates							
Ghana	10.00[n]						
Kenya	6.90[n]						
Malawi	9.00[n]						
Nigeria	6.86[n]						

Tanzania	10.00[n]
Tunisia	10.70[n]

Notes:

[a] *hours. A generator lifespan depends on various factors, such as generator and fuel type, size, and usage (UL Solutions, 2024). HOMER estimates up to 10,000 hours for smaller units (≤50 kW) and 20,000-80,000 hours for prime power, liquid-cooled systems. A 20,000-hour lifespan is assumed here for simplicity.*

[b] *years. The lifespan of a gasifier can range between 15-30 years (Agapova et al., 2024). The life expectancy of a boiler is estimated at 20 years (IRENA Secretariat, 2012), while the lifespan of stoves, kilns and burners are estimated at 10 years (Mindjimba, 2020; Shaik et al., 2022). Standard values for the lifespan of solar PV systems and inverters are taken into consideration, whereby solar PV system is estimated to have a life expectancy of 25 years, and inverters of 15 years (Idbouhouch et al., 2024; Sodhi et al., 2022). Lead acid and lithium-ion batteries are assumed to last 5 and 10 years, respectively before they need to be replaced (Kebede et al., 2021; C. Zhang et al., 2017).*

[c] *USD/unit. In Ghana, the costs of kilns and stoves vary from 41 USD/unit for charcoal and firewood kilns, to 67 USD/unit for FAO-FTT kilns, 74 USD/unit for LPG kilns, and similarly 75 USD/unit for LPG stoves* (Nyemah & Rotawewa, 2021; Ogundana et al., 2022; Organization of the Petroleum Exporting Countries (OPEC) Fund for International Development, 2024). *In Nigeria, 25 USD/unit refers to an LPG Bunsen burner. In Tanzania, it is assumed that cookstoves based on traditional biomass (charcoal and firewood) account for 15 USD/unit* (Jeuland & Pattanayak, 2012)*, and LPG stoves cost 66 USD/unit* (The United Republic of Tanzania & Ministry of Energy, 2024).

[d] *USD/kW$_p$, including hardware (e.g., panels, inverter), installation, soft costs, and taxes. Country-specific cost estimates were used (ESMAP, 2022). However, for Malawi quotations from suppliers obtained from a GIZ representative of a Malawian project were used, while for Tunisia actual costs incurred by the entrepreneur were used to estimate additional solar PV CAPEX.*

[e] *USD/kW. Inverter costs represent replacement costs and are estimated based on average values as indicated by the Energy Sector Management Assistance Program (2022). The only exception is Malawi, where inverter costs were given by quotation from suppliers. Generator costs are generally estimated at 600 USD/kW based on Homer Pro data (UL Solutions, 2024). In Malawi, it is further assumed that a dual fuel generator running on diesel and syngas would incur costs of 568 USD/kW (author estimation based on some insights from PwC (2024) regarding potential taxation. Gasifier costs are estimates from Lourinho et al. (2023). In Kenya, 3,070 USD/kW refers to a biomass briquette boiler (IRENA Secretariat, 2012), while the cost of a biogas boiler is*

incorporated in the total AD system costs, in which the boiler is assumed to contribute 15% of the total AD system CAPEX (Mezzadri & Francescato, 2014).

[f] *USD/kWh. Battery costs are assumed as per the Energy Sector Management Assistance Program (2022) and were estimated either based on the respective country value or, if that data was not available, based on the Africa/Asia average value.*

[g] *USD/kW_p/year are standard estimates for solar PV systems (ESMAP, 2022).*

[h] *USD/kWh/year are standard estimates for solar PV systems (ESMAP, 2022).*

[i] *USD/operating hour/kW. A value of 0.03 USD/operating hour/kW is a default value in Homer Pro (UL Solutions, 2024). In Malawi, a 33% increase was assumed, while in Tunisia, the value represents the cost of hiring labour as per the interview data.*

[j] *USD/kW/year. The O&M costs of a gasifier consist of 4.5% of CAPEX and 3.54 USD/MWh (Lourinho et al., 2023). The O&M costs of a biomass briquette boiler consist of 3-6% of CAPEX and 4.25 USD/MWh (IRENA Secretariat, 2012).*

[k] *USD¢/kWh. Electricity tariffs are based on published tariffs by the country's respective regulatory energy authority, inclusive of taxes, levies, and energy charges (ESCOM, 2021; EPRA, 2023; KPLC, 2023; NERC, 2024; PURC, 2023; STEG, 2022).*

[l] *USD/L. Fuel prices are based on interview data* (Gad & Leone, 2025).

[m] *USD/kg. Fuel prices are based on interview data* (Gad & Leone, 2025). *Additional references were used to estimate the costs of coconut husks (Ndiaye et al., 2015) and maize residues (IRENA Secretariat, 2012).*

[n] *Nominal discount rates are based on literature values for renewable energy projects in the respective country* (Afful-Dadzie et al., 2022; Borgstein et al., 2019; Mas'ud et al., 2024; Odoi-Yorke & Woenagnon, 2021; Osei et al., 2024; Saddari et al., 2025; Taylor et al., 2023; Zigah et al., 2023).

Abbreviations: CAPEX = capital expenditures; kW = kilowatt; kWh = kilowatt-hour; kW_p = kilowatt peak; LPG = liquified petroleum gas; PV = solar photovoltaic; USD = United States dollar

Table D.2a. Case study 1: Techno-economic assumptions and parameters of the base case

	Value	Unit	Reference
Economic parameters			
Grid tariff	0.1357	USD/kWh	(PURC, 2023)
LPG costs	0.8747	USD/L	(Gad & Leone, 2025)
Charcoal cost	0.3490	USD/kg	(Gad & Leone, 2025)
Firewood cost	0.0907	USD/kg	(Gad & Leone, 2025)
Exchange rate	11.02	GHS/USD	(Central Bank of Ghana, 2023)
Cost of LPG kiln (and replacement)	74.26	USD/unit	(Nyemah & Rotawewa, 2021; Ogundana et al., 2022)
Cost of firewood/charcoal kiln replacement	41.28	USD/unit	(Nyemah & Rotawewa, 2021; Ogundana et al., 2022)
Cost of LPG stove (and replacement)	75	USD/unit	(OPEC Fund for International Development, 2024)

Lifespan of stove and kiln	10	years	(Mindjimba, 2020; Shaik et al., 2022a)

Productive use data

Monthly grid electricity demand	72.61	kWh/month	(Gad & Leone, 2025)
Monthly LPG stove demand	37.45	kWh/month	(Gad & Leone, 2025)
Monthly LPG kiln demand	31.20	kWh/month	(Gad & Leone, 2025)
Monthly charcoal kiln demand	78.12	kWh/month	(Gad & Leone, 2025)
Monthly firewood kiln demand	114.40	kWh/month	(Gad & Leone, 2025)
Monthly total thermal demand	261.17	kWh/month	(Gad & Leone, 2025)
Days of operation per year	260	days/year	(Gad & Leone, 2025)

Daily demand profile

Equipment	Power (kW)	Use (h/day)	Days/week	Time of use
2x Freezer	0.26	5	5	Split evenly throughout the day
Milling device	0.2	1	5	15-16:00
Mixing device	0.2	3	5	12-15:00

LPG stove	0.86	2	1	12-14:00
LPG kiln	0.33	24	1	4 days/month, 24 h/day
Charcoal kiln	2.44	8	1	4 days/month, 9-17:00
Firewood kiln	3.58	8	1	4 days/month, 9-17:00

Abbreviations: GHS = Ghanaian Cedi; h = hour(s); kg = kilogramme; kW = kilowatt; kWh = kilowatt-hour; L = litre; LPG = liquified petroleum gas; USD = United States dollar

Table D.2b. Case study 1: Techno-economic assumptions and parameters of scenario 1

	Value	Unit	Reference
Economic parameters			
Non-residential net metering tariff (capacity charge (import), excluding service charge, levies and taxes	0.0753	USD/kWh	(PURC, 2022)
Non-residential net metering tariff (energy charge (export), excluding service charge, levies and taxes	0.0502	USD/kWh	(PURC, 2022)
Non-residential net metering tariff (retail tariff), excluding service charge, levies and taxes	0.1256	USD/kWh	(PURC, 2022)
Service charge	1.13	USD/month	(PURC, 2022)
Levies and taxes	29.00	% of import fee	(PURC, 2022)
LPG costs	0.8747	USD/L	(Gad & Leone, 2025)

Exchange rate	11.02	GHS/USD	(Central Bank of Ghana, 2023)
Cost of a bidirectional meter	277.5	USD/unit	(Roux & Shanker, 2018)
CAPEX solar PV	1,596	USD/kW_p	(ESMAP, 2022)
Productive use data			
Yearly grid electricity purchased	551	kWh/year	(Gad & Leone, 2025)
Yearly electricity sold	1,057	kWh/year	(Gad & Leone, 2025)
Yearly electric demand	871	kWh/year	(Gad & Leone, 2025)
Yearly LPG demand	790	L/year	(Gad & Leone, 2025)
Yearly thermal demand	3,134	kWh/year	(Gad & Leone, 2025)

Abbreviations: % = percent; CAPEX = capital expenditure; GHS = Ghanaian Cedi; h = hour(s); kW = kilowatt; kWh = kilowatt-hour; L = litre; LPG = liquified petroleum gas; USD = United States dollar

Table D.3. Case study 3: Techno-economic assumptions and parameters of the base case

	Value	Unit	Reference
Economic parameters			
Grid tariff	0.1768	USD/kWh	EPRA, 2023; KPLC, 2023
Diesel cost	1.20	USD/L	Gad & Leone, 2025
Briquette cost	0.011	USD/kg	Gad & Leone, 2025
O&M of diesel generator	0.03	USD/kW/operating hour	UL Solutions, 2024
Cost of biomass briquette boiler replacement	3,070	USD/kW	IRENA Secretariat, 2012
Fixed O&M costs of the boiler	138.15	USD/kW	IRENA Secretariat, 2012
Variable O&M costs of the boiler	4.25	USD/MWh	IRENA Secretariat, 2012
Exchange rate	139.35	KES/USD	Central Bank of Kenya, 2023
Productive use data of the dairy plant			

Monthly grid electricity demand	3,302	kWh/month	Gad & Leone, 2025
Monthly solar PV demand	3,450	kWh/month	Gad & Leone, 2025
Monthly backup electric demand	359	kWh/month	Gad & Leone, 2025
Monthly thermal demand	130,130	kWh/month	Gad & Leone, 2025
Days of operation per year	365	days/year	Gad & Leone, 2025

Daily demand profile at the dairy plant

Equipment	Power (kW)	Use (h/day)	Days/week	Time of use
1x Can scrubber	3	1	7	9-10:00
1x Humidity controller	10	1	7	9-10:00
1x Water chiller	50	2	7	10-12:00
1x Particle filter	2	3	7	11-14:00
1x Cream separator	7.5	1	7	12-13:00
1x Homogeniser	30	1	7	12-13:00
1x Pasteuriser	14.92	3	7	13-16:00

1x Equipment cleaner	7.5	2	7	15-17:00
1x Cooling storage unit	3.50	5	7	Split into 5h/day

Productive use data of the cereal milling facility

Monthly grid electricity demand	30,940	kWh/month	Gad & Leone, 2025
Days of operation per year	260	days/year	Gad & Leone, 2025

Demand profile at the cereal milling facility

Equipment	Power (kW)	Use (h/day)	Days/week	Time of use
1x Maize mill	75.00	12	5	7-19:00
1x Animal feed	40.00	8	5	9-17:00
1x Hammer mill	22.00	8	5	9-17:00
1x Mixer	4.00	8	5	9-17:00

Notes: At the dairy plant, certain processes involving equipment that has already been purchased and installed but is currently not in use have been excluded from the base case. This applies to the butter churn and ripening unit (6 kW capacity), as well as the yoghurt and milk packaging devices (7.5 kW and 20 kW capacities, respectively). As these do not form part of the base case scenario, their associated costs and energy consumption have not been considered.

Abbreviations: h = hour; KES = Kenyan shillings; kg = kilogramme, kW = kilowatt; kWh = kilowatt-hour; L = litre; USD = United States dollar

Table D.4. Case study 5: Techno-economic assumptions and parameters of the base case

	Value	Unit	Reference
Economic parameters			
Grid tariff	0.1394	USD/kWh	Nigerian Electricity Regulatory Commission, 2024
LPG costs	0.6125	USD/L	Gad & Leone, 2025
Petrol cost	0.6919	USD/L	Gad & Leone, 2025
Diesel cost	0.7429	USD/L	Gad & Leone, 2025
Cost of generator replacement	600	USD/kW	UL Solutions, 2024
Generator O&M costs	0.03	USD/kW/operating hour	UL Solutions, 2024
Exchange rate	1615.25	N/USD	Central Bank of Nigeria, 2023
Productive use data of the production site			
Monthly grid electricity demand	199.81	kWh/month	Gad & Leone, 2025

Monthly electric demand supplied by a backup generator	148.74	kWh/month	Gad & Leone, 2025
Monthly thermal demand	56.17	kWh/month	Gad & Leone, 2025
Days of operation per year	260	days/year	Gad & Leone, 2025

Daily demand profile at the production site

Equipment	Power (kW)	Use (h/day)	Days/week	Time of use
Blow dryer	2	1	5	1x/day (afternoon)
Iron	0.8	2	5	Split into two non-overlapping slots (morning + afternoon)
Stamping machine	0.8	1	2	Assumed afternoon
Overlock	0.25	2	4	Split into two non-overlapping slots (morning + afternoon)
2x Sewing machines	0.5	3	4	Between 13-16:00
2x Filler machines	1.1	5	5	Split into two blocks (2h morning + 3h afternoon)
Daily base load	0.63	8	5	Split evenly throughout the day
Daily total thermal demand	1.62	2	4	Split into two non-overlapping slots (morning)

Productive use data of the retail shop			
Monthly grid electricity demand	177.65	kWh/month	Gad & Leone, 2025
Monthly backup electric demand	1,128.75	kWh/month	Gad & Leone, 2025
Days of operation per year	312	days/year	Gad & Leone, 2025

Demand profile at the retail shop

Equipment	Power (kW)	Use (h/day)	Days/week	Time of use
3x AC	3.36	8	6	Split evenly throughout the day
1x AC	0.75	8	6	Split evenly throughout the day
1x refrigerator	0.3	6	7	Base load, split into 5h/day of operation
Daily base load (lights, office equipment)	1.67	8	6	Split evenly throughout the day

Abbreviations: AC = air conditioner; h = hour; kW = kilowatt; kWh = kilowatt-hour; L = litre; LPG = liquified petroleum gas; N = Nigerian Naira; USD = United States dollar

Table D.5a. Case study 6: Assumptions and parameters for scenario 2

	Value	Unit	References
Economic parameters and assumptions			
Cost of a biogas stove	66.25	USD/unit	(The United Republic of Tanzania Ministry of Energy, 2024)
Biogas stove lifespan	10	years	(Mindjimba, 2020; Shaik et al., 2022)
CAPEX AD	186.33	USD/m^3 of AD capacity	(Energy and Environment Partnership, 2019)
Cost of a biogas upgrading unit	2,175.00	USD/m^3-h	(Suliman, 2022)
Cost biomethane compressor	27,048	USD/unit	(Alibaba.com, 2025; Ferrari et al., 2024; PwC, 2025)
O&M AD	15.00	USD/year, starting in year 6	(Energy and Environment Partnership, 2019)
O&M biogas upgrading	54.38	USD/(m^3/h)/year	(Bauer et al., 2013)
O&M biomethane compression	676.20	USD/year	(Bauer et al., 2013)
O&M logistics	17.52	USD/truck/trip	Mywage.org/Tanzania, 2025)
Cost of an 8-bar cylinder	46	USD/unit	(The United Republic of Tanzania Ministry of Energy, 2024)

Cost of a 200-bar cylinder	90	USD/unit	(Alibaba.com, 2025b; PwC, 2025)
Cost of generator fit for biomethane combustion	600	USD/kW	(UL Solutions, 2024)
O&M generator	0.03	USD/kW/operating hour	(UL Solutions, 2024)
Biogas-related parameters and assumptions			
Wastewater volume	7,000	L/day	(Gad & Leone, 2025)
HRT	24.25	days	(Martí-Herrero et al., 2018)
COD removal efficiency	77.80	%	(Martí-Herrero et al., 2018)
Methane yield	0.36	m^3 CH_4/kg COD	(Martí-Herrero et al., 2018)
Methane content in biogas	55.05	%	(Martí-Herrero et al., 2018)
Methane energy content	10.00	kWh/m^3	(Cappannelli et al., 2020)
COD concentration	4,400	mg/L	(Bhunia et al., 2022)
Days to fill the intermittent storage tank	10.00	days	Author's assumption
Upgrading- and compression-related parameters and assumptions			
Discharge pressure of first compressor	8	bar	Author's assumption

Discharge pressure of second compressor	200	bar	Author's assumption
Energy consumption for biogas upgrading (first compressor, pump, cooling)	0.23	kWh/m^3 biogas entering	(Bauer et al., 2013)
Energy consumption for biomethane compression	0.19	kWh/m^3 biogas entering	(Noussan et al., 2024)
Methane losses from upgrading	1.97	%	(Kvist & Aryal, 2019)
Hours of upgrading operation	8.00	h/day	(Ilyas, 2006)
Molecular weight of biomethane	16.00	g/mol	(Lauri, 2023)
Ambient temperature, around 25°C	298.00	K	(Lauri, 2023)
Gas constant	8.314	J/mol-K	(Lauri, 2023
Storage- and transportation-related parameters and assumptions			
Fuel consumption of a road freight truck	0.01327	L of diesel/tonne-km	(Abiero et al., 2015)
Round-trip distance	100.00	km/truck	Author's assumption
Truck tare weight	3.00	tonne/truck	(Taifa Gas, 2024)
Truckload capacity	8.00	tonne/truck	(Taifa Gas, 2024)
Fuel costs of diesel	1.24	USD/L	(EPRA, 2023)

8-bar cylinder capacity	0.030	m^3	(Mathesongas, n.d.)
200-bar cylinder capacity	0.044	m^3	(Mathesongas, n.d.)
8-bar cylinder tare weight	22.00	kg	(Mathesongas, n.d.)
200-bar cylinder tare weight	84.60	kg	(Mathesongas, n.d.)
Biomethane to electricity conversion-related parameters and assumptions			
Generator nominal electrical efficiency running on biomethane	35	%	Ciuła et al., 2022; Kabeyi & Olanrewaju, 2022
Generator lifetime	20,000	h	UL Solutions, 2024

Abbreviations: % = percent; °C = degree Celsius; AD = anaerobic digester; h = hour; HRT = hydraulic retention time; J/mol-K = Joule per moles Kelvin; K = Kelvin; kg = kilogramme; km = kilometre; kW = kilowatt; kWh = kilowatt-hour; m^3 = cubic meter; m^3/h = cubic meter per hour; m^3/kg FM = cubic meter per kilogramme fresh matter; m^3 CH_4/kg COD = cubic meter methane per kilogramme chemical oxygen demand; L = litre; MJ/kg = megajoule per kilogramme; USD = United States dollar

Table D.5b. Case study 6: Assumptions and parameters for scenario 3

	Value	Unit	References
Economic parameters and assumptions			
Biogas stove	66.25	USD/unit	(The United Republic of Tanzania Ministry of Energy, 2024)
Biogas stove lifespan	10	years	(Mindjimba, 2020; Shaik et al., 2022)
Total CAPEX AD system	207.04	USD/m^3 of AD storage capacity	(Energy and Environment Partnership, 2019)
CAPEX AD	186.33	USD/m^3 of AD storage capacity	(Energy and Environment Partnership, 2019)
CAPEX biogas cleaning unit	10	% of total AD CAPEX	Choudhury et al., 2019)
O&M AD	15.00	USD/year, starting in year 6	(Energy and Environment Partnership, 2019)
O&M biogas cleaning	0.028	USD/m^3 biogas cleaned/year	(Choudhury et al., 2019)
O&M logistics	17.52	USD/truck/trip	(Mywage.org/Tanzania, 2025)
Cost of generator fit for biogas combustion	600	USD/kW	(UL Solutions, 2024)
O&M generator	0.03	USD/kW/operating hour	(UL Solutions, 2024)
Diesel costs	1.24	USD/L	(EPRA, 2023)

Biogas-related parameters and assumptions			
HRT	25	days	(Bhave & Patil, 2022; Elango et al., 2007)
LHV biogas	22	MJ/m^3	(Cappannelli et al., 2020)
Density biogas	1.15	kg/m^3	(Jørgensen, 2009)
Biogas energy content	6	kWh/m^3	(Cappannelli et al., 2020)
Biogas yield from MSW	0.092	m^3/kg FM	(LfL, n.d.)
Biogas to electricity conversion-related parameters and assumptions			
Generator nominal electrical efficiency running on biogas	30.00	%	(Ciuła et al., 2022; Kabeyi & Olanrewaju, 2022)
Peak load to be covered by the generator	2	kW	(Gad & Leone, 2025)
Contingency to be added to the size generator	20.00	%	Author's assumption
Biogas cleaning-related parameters and assumptions			
Flow rate of biogas entering the cleaning unit	20	m^3/h	Author's assumption
Operation time of the cleaning unit	1	h/cycle	Author's assumption
Electrical energy consumption of the cleaning unit	0.0053	$kWh/(m^3\text{-}h)$	(Allegue & Hinge, 2014)

Transport of MSW-related parameters and assumptions			
Density of food waste	202	kg/m^3	(Li et al., 2021)
Total household food waste produced per capita in Dar es Salaam	0.35	kg/capita/day	(UN-Habitat, 2021)
Average household size in Dar es Salaam	3.5	persons	(The United Republic of Tanzania et al., 2022)
Population density Dar es Salaam	3,865	persons/km^2	(The United Republic of Tanzania et al., 2022)
Fuel consumption of a road freight truck	0.01327	L of diesel/tonne-km	(Abiero et al., 2015)
Truck tare weight	1.50	tonne/truck	(Taifa Gas, 2024)
Truck movements	26.00	times/year	Author's assumption

Abbreviations: % = percent; AD = anaerobic digester; HRT = hydraulic retention time; kg = kilogramme; km = kilometre; km^2 = square kilometre; kW = kilowatt; kWh = kilowatt-hour; m^3/kg *FM = cubic meter per kilogramme fresh matter; L = litre; MJ/kg = megajoule per kilogramme; USD = United States dollar*