From standalone to interconnected: Sector-coupled optimisation of La Gomera’s renewable energy portfolio for integrated energy planning

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From standalone to interconnected: Sector-coupled optimisation of La Gomera's renewable energy portfolio for integrated energy planning

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A R T I C L E I N F O

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A B S T R A C T

Small islands offer unique opportunities to test and implement energy system decarbonisation strategies. Their isolation provides a controlled setting to analyse renewable integration, sector coupling, and grid flexibility, while their reliance on imported fossil fuels highlights the urgency of transition. La Gomera, an island in the Canary Archipelago (Spain), represents a strategic case study given its ongoing shift away from conventional fuels and its planned interconnection with Tenerife. This study develops a replicable framework for small island decarbonisation planning, combining EnergyPLAN simulations with a MATLAB-based optimisation routine. A stepwise modelling strategy was applied, progressively expanding the system from a stand-alone configuration to increasingly complex scenarios. Initial optimisation focused on photovoltaic and wind capacities, followed by the introduction of: (i) a subsea cable to Tenerife; (ii) a waste-to energy facility; (iii) battery energy storage; and (iv) transport electrification at varying penetration levels. Each phase was re-optimised to reflect updated system conditions. A simplified representation of Tenerife's electricity demand was integrated to assess interconnection performance and explore the role of offshore floating wind power generation. The results demonstrate that, even under conservative assumptions, optimised renewable portfolios for La Gomera are economically competitive and enable significant emission reductions. Interconnection and cross-sectoral coordination emerged as key enablers of system flexibility and renewable utilisation. While the analysed scenarios are subject to spatial and regulatory constraints, they provide a robust foundation for long-term planning. The methodology proposed here is transferable to other insular regions, offering a pathway towards resilient, integrated, and decarbonised energy systems.

1. Introduction

In terms of energy supply, the vast majority of populated islands depend on imported fossil fuels, which are typically unavailable locally [1]. For over three decades, the European Union (EU), in collaboration with national and local authorities, has sought to transform this structural dependency into an opportunity by developing sustainable transition programmes, thereby positioning European islands as key actors in advancing sustainable development strategies.

Several intrinsic characteristics explain why islands are particularly suitable for such initiatives. Their relatively small scale allows for a complete representation of the entire power system and facilitates the rapid deployment, commissioning, and assessment of innovative technology mixes. In addition, the vertical integration of local utilities and the strong cohesion of local communities provide a favourable environment for consumer engagement and for rethinking the energy system (ES) from generation mix to user behaviour [2]. These aspects, combined with often favourable climatic conditions for renewable generation and the high levelised cost of electricity (LCOE) associated with diesel imports [3], make islands effective testbeds for transition pathways that can subsequently be scaled up and replicated in larger systems.

However, the integration of renewables into isolated ESs presents specific challenges, primarily due to the intermittent nature of most renewable energy sources (RESs). Issues such as grid stability and the mismatch between electricity supply and demand become increasingly critical as the share of renewable generation increases. To achieve a

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fully RES-based ES it is necessary to address all the fuel-consuming sectors. In the electricity sector, fossil-fuel generation must be entirely replaced by renewables, but this alone is insufficient. In the transport sector, internal combustion engine vehicles need to be replaced by battery electric vehicles (EVs), biofuel-powered vehicles, or alternative solutions such as hydrogen. If electrification is chosen as the preferred pathway, vehicle-to-grid (V2G) technology could support system flexibility and enable a more effective use of intermittent renewable sources, although even in this case a complete rethinking of the system architecture is required [4].

From a political perspective, the strategic relevance of island power systems is underscored by the fact that more than one hundred European islands operate with non-interconnected electricity networks, and recognised by project as the *Clean energy for EU islands* initiative [5], which aim is to support the EU islands in their energy transition. Overall, this initiative confirm the EU's long-term commitment to turning the geographic constraints of islands into an advantage, leveraging their unique features to position them as demonstrators of the feasibility of future clean ESs.

1.1. Literature overview on sector-coupled energy planning optimisation and interconnection-oriented island transitions

Over the last decade, integrated energy planning has increasingly relied on optimisation workflows, where a detailed simulator is used to evaluate candidate system configurations and an external optimisation layer explores the design space. This paradigm is particularly attractive for smart energy systems (SES) and sector-coupled studies because it easily enables the representation of technology interactions and operational logics. Within this context, EnergyPLAN has become a widely adopted simulation core for SES analysis and is frequently coupled with external routines (*e.g.*, MATLAB) to support systematic scenario exploration, optimisation, and multi-criteria assessment [6]. Recent overview works further confirm the maturity and breadth of sector-coupled planning research [7] and highlight the need for transparent indicators and decision-oriented workflows [8]. Starting from this basis, different works focus on moving beyond deterministic scenario comparisons by embedding EnergyPLAN within structured exploration or explicit optimisation routines. Pastore et al. [9] propose a SES-oriented methodology to support national planning under strengthened EU targets, implementing a systematic cross-sector exploration in MATLAB. The same research line extends to a long-term 100% decarbonisation vision, emphasising the role of cross-sector flexibility and power-to-x options in reducing curtailment and improving system efficiency [10]. Doepfert and Castro [11] implement a metaheuristic optimisation coupled with EnergyPLAN simulation for a 100% renewable system design in Portugal, highlighting how resource variability can affect optimal portfolios. At smaller scales, sector coupling is used as a practical flexibility lever: Pastore [12] compares power-to-heat and power-to-vehicle strategies in smart urban districts, while Hoseinzadeh et al. [13] derive 50% and 100% renewable urban scenarios.

The island domain constitutes a particularly stringent and interesting application for optimal SES planning because it concentrates typical decarbonisation constraints (high costs, limited inertia, strong RES variability and limited flexibility) within a clear system boundary. Groppi et al. [14] compare SES simulation tools to model and plan the energy transition of a small Mediterranean island. Building on this context, optimisation wrappers have been proposed to automate and broaden the exploration of island portfolios: EPLANopt is introduced and demonstrated for Favignana island to derive Pareto-optimal technology configurations under multi-objective criteria [15], and EPLANoptMAC extends this framework to include the maritime transport sector by embedding EnergyPLAN with a marginal abatement cost curve in order to drive the energy system optimisation [16]. These works demonstrate that island energy planning increasingly relies on structured optimisation and explicit trade-off analysis rather than on hand-crafted scenarios alone. Complementary research emphasises the role of system flexibility and demand-side strategies. Neves et al. [17] discuss how flexible demand response modelling differs across commonly used tools and how such differences can propagate into planning outcomes. Pfeifer et al. [18] analyse the system flexibility by the perspective of the integration of renewables and demand response technologies in interconnected island systems, using EnergyPLAN and MultiNode, showing that flexible strategies can complement interconnection benefits to increase feasible renewable shares and reduce fossil backup needs. Broader island studies extend the boundary beyond electricity by explicitly modelling additional sectors and infrastructures. Coupling the energy system with water services (*e.g.*, desalination) adds flexibility and affects renewable integration [19]. Instead in [20], a stepwise strategy framework is proposed to progressively approach near-100% renewable operation at system scale. Including maritime transport can change feasibility and optimal pathways [21]. Moreover, high-renewable cases under transport electrification are validated via additional security/stability checks [22]. Finally, Galapagos-focused studies assess deep decarbonisation feasibility scenarios [23], and a recent review summarises the current status and key aspects to higher renewable shares in that area [24]. In conclusion, Ramos-Marin and Guedes Soares [25] explicitly compare multi-objective optimisation algorithms in a remote-island setting and include marine/offshore resources (*e.g.*, wave and offshore wind), reinforcing the value of Pareto-based approaches when multiple competing indicators must be balanced. Inter-island interconnections are increasingly discussed as structural enablers for high-RES archipelagos, because they expand balancing areas and can reduce the need for local overcapacity. Recent archipelago-level analyses highlight that coordinated reinforcement and interconnection planning can significantly affect the required generation and storage mix in deep decarbonisation scenarios [26]. Crucially, [27] explicitly assesses the projected Tenerife-La Gomera interconnection, in the Canary archipelago, by comparing it against an alternative pathway in which La Gomera develops as an isolated system with high renewable and storage deployment, quantifying implications in terms of costs and emissions.

The literature summarised in Table 1 confirms the maturity of sector-coupled planning for SES, while also revealing that inter-island interconnections are still rarely integrated as an explicit design lever within optimisation workflows. Instead, cables are typically assumed as fixed infrastructure and evaluated ex-post via scenario comparisons (e.g., [26]) rather than co-designed with local RES and storage portfolios. Two gaps therefore remain salient: limited evidence on optimisation frameworks where the introduction of interconnection reshapes the optimal portfolio, and scarce operationally consistent quantification of how cable sizing affects utilisation and system flexibility. The present paper addresses these gaps by explicitly embedding the planned La Gomera–Tenerife interconnection into the simulation-optimisation loop (including a simplified representation of Tenerife demand) and by using multi-objective indicators to expose trade-offs among deep decarbonisation, mismatch/oversizing proxies, storage needs and interconnection utilisation.

1.2. Motivation, novelty and contribution of the paper

Small and isolated energy systems face transition challenges (due to their fuel-import dependence, high electricity costs, and vulnerability to supply disruptions) yet their limited scale and resource availability make them suitable testbeds for replicable decarbonisation strategies. La Gomera (Canary Islands) is an exemplary case, with new renewables already deployed and an imminent subsea interconnection to Tenerife via a subsea cable, enabling integrated planning under realistic boundary conditions. Building on the gaps highlighted in Section 1.1, the novelty of this work lies in the formulation and application of a stepwise optimisation workflow explicitly structured

Table 1
Compact classification of reviewed literature. Legend: grey indicates a negative outcome (criterion not satisfied), green indicates a positive check (criterion satisfied), and yellow indicates partial compliance (criterion only partially satisfied), *i.e.*, the study explores multiple configurations rather than performing a formally defined optimisation.

Reference	Case study	RES portfolio optimisation	Islands' interconnection
[9]	Italy	~	
[10]	Italy	✓	
[11]	Portugal	✓	
[12]	Rome	~	
[13]	Ragusa	~	
[14]	Favignana	✓	
[15]	Favignana	✓	
[16]	Favignana	✓	
[17]	Corvo Island		
[18]	Croatia islands		✓
[19]	Lanzarote	✓	
[20]	Gran Canaria	~	
[21]	Sardinia		
[22]	Gran Canaria	✓	
[23]	Galapagos	✓	
[24]	Galapagos		
[25]	Porto Santo	✓	
[26]	Canary Islands	✓	✓
[27]	Canary Islands		✓
This work	La Gomera	✓	✓

around an interconnection-driven transition. The system is progressively expanded from an isolated configuration to increasingly complex planning stages, while the planned La Gomera–Tenerife link is explicitly embedded into the simulation-optimisation loop through a simplified representation of Tenerife demand. The cable size is subsequently treated as a design variable to explore the interplay between export capability and interconnection exploitation in enabling high renewable penetration in the system. The main contribution of this study is the development of an integrated optimisation framework to identify decarbonisation pathways for islands, applied to the La Gomera energy system case study. A cross-sector reinforcement logic is adopted to evaluate complementary flexibility and decarbonisation levers across electricity, transport and heating. The key methodological novelty is the interconnection-centred formulation, which enables a quantitative assessment of how a grid link to Tenerife influences renewable utilisation, system balancing, and the interaction between cable sizing and the selected technology portfolio. Finally, an a posteriori techno-economic assessment of selected Pareto-optimal portfolios translates technically feasible solutions into comparable economic metrics. Overall, the paper aims to support policymakers and system planners by clarifying trade-offs between deep decarbonisation, mismatch/oversizing proxies, storage needs, and interconnection utilisation, and providing a transparent basis for comparing near-term and medium-term transition pathways in small island contexts undergoing imminent infrastructure changes.

1.3. Structure of the paper

The remainder of the paper is organised as follows. Section 2 describes the methodology employed, including the modelling environment, the optimisation framework, and the EnergyPLAN–MATLAB routine. Section 3 presents the reference energy system model, its formulation, and the input data used, while Section 4 provides the formulation of the optimisation problem. Section 5 details the case study of La Gomera, discussing the reference scenarios, its validation, and the context of the planned interconnection with Tenerife. The optimisation results are presented and discussed in Section 6, where increasingly complex configurations are analysed, including stand-alone, interconnected, and sector-coupled systems. Section 7 integrates the techno-economic analysis of representative scenarios, linking investment requirements with system-level benefits. Finally, Section 9 draws the main conclusions, outlines the limitations of the current work, and suggests avenues for future research.

1.4. Notation

The notation adopted throughout this paper can be summarised as follows. The symbol $\mathbb{R}$ denotes the set of real numbers, while $\mathbb{C}$ represents the set of complex numbers, with Re and Im indicating their real and imaginary parts, respectively. The imaginary unit is denoted by j. Any null element, regardless of its dimension, is represented by 0. The set of positive natural numbers up to n is defined as $\mathbb{N}_n = \{1, 2, \ldots, n\}$. Matrices and vectors are indicated by bold letters. Given a matrix $\mathbf{M} \in \mathbb{R}^{r\times c}$ of dimension r rows and c columns, its (a, b)-th entry is denoted as $M_{a,b}$, where $a \in \mathbb{N}_r$ and $b \in \mathbb{N}_c$. Similarly, for a vector $\mathbf{v} \in \mathbb{R}^s$ with s components, the ath entry is denoted as v_a with $a \in \mathbb{N}_s$. The transpose operator is indicated by the superscript ^{T}. Finally, the normalisation of a vector with respect to the maximum of its elements (*e.g.* the peak value of a time series) is denoted by the symbol $\hat{\cdot}$.

2. Methodology

The energy transition requires the development of customised, multi-sectoral plans capable of addressing the complexities of interconnected ESs while ensuring operational stability and grid security. Maximising renewable penetration calls for the adoption of sector-specific strategies, potentially in stand-alone configurations, to guarantee continuity of supply while accounting for both technical and economic aspects. To inform and support such ES planning, different ES modelling tools have been developed. Those tools are designed to represent supply and demand dynamics across one or multiple sectors. Models are commonly classified along two principal axes: bottom-up vs. top-down [28], and simulation vs. optimisation approaches [29]. Bottom-up (engineering) models incorporate detailed technological characterisation, whereas top-down models embed the energy sector within a broader macroeconomic framework [30]. Additional classification criteria include sectoral coverage, spatial resolution, and methodological structure [31]. Each approach involves trade-offs: optimisation models identify cost-minimal pathways but may be complex to interpret, while simulation models provide operational detail but rely on fixed assumptions, and equilibrium models capture economy-wide interactions at the expense of technical resolution [29]. For a deeper overview of the present ES model, tools and their classification, interested readers are referred to [28].

The methodology adopted for this study refers to and adapts the design process used in previous studies developed by Cabrera et al. for

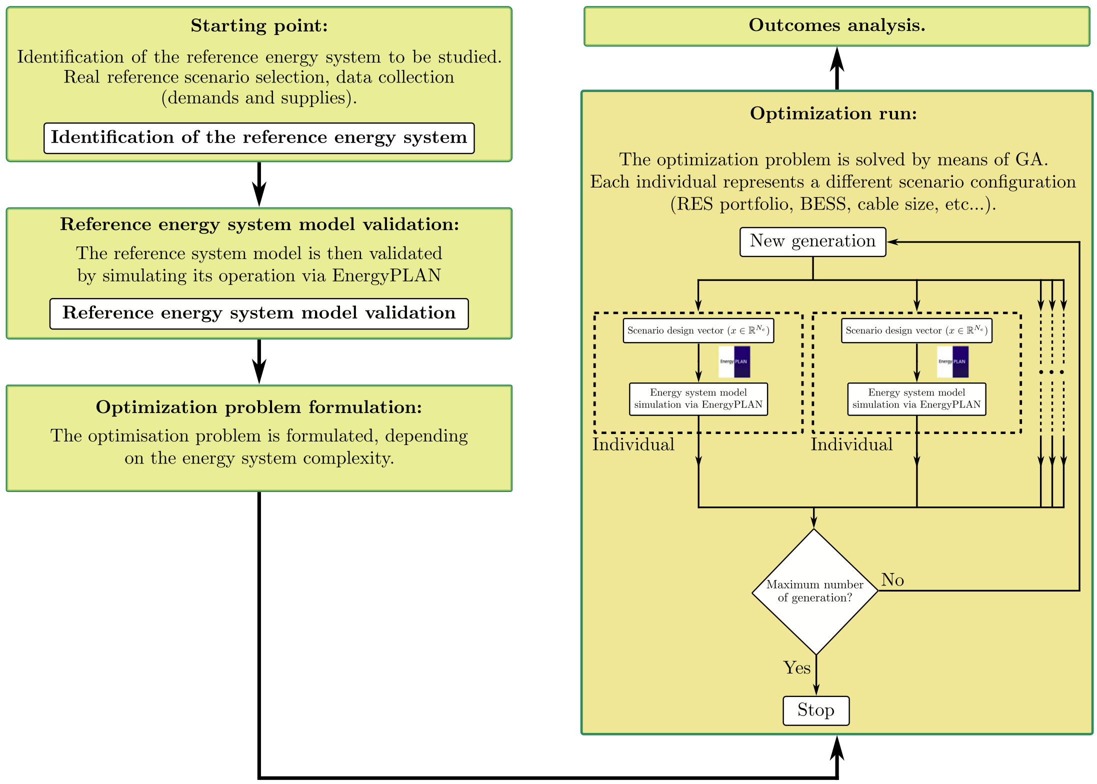


Fig. 1. Schematisation of the approach employed in the present study.

Gran Canaria [20] and Lazarote [19], which employ the EnergyPLAN tool. An introduction to EnergyPLAN, highlighting the main features for which this tool was chosen, is given in Section 2.1, while the steps of the employed framework are outlined below:

1. The process begins with identification of the reference ES to be studied. A real reference scenario is selected and its key aspects identified, based on collected data and reports.
2. The reference system model is then validated by simulating its operation with EnergyPLAN. The model is adjusted until the output results align with the collected data.
3. The core of the study involves implementing changes in the sectors of interest and formulating different optimisation problems with the aim of searching for the optimal RES portfolio in each case. The study is conceived of as an increasingly structured model, in which new aspects are implemented and refined in a step-by-step manner, making the system more robust in terms of the number of sectors involved and therefore also the achieved solutions. In this work, the optimisation processes are carried out in the MATLAB environment, which interacts directly with the ES model by means of the EnergyPLAN MATLAB toolbox [32].
4. The results of each step are analysed and critically evaluated, including comparisons with the baseline scenario and the other alternative scenarios under consideration.
5. Finally, specific scenarios of particular relevance are selected and further analysed from a techno-economic perspective.

Fig. 1 depicts the flowchart of the employed methodology.

2.1. EnergyPLAN modelling tool

As previously mentioned, this study employs EnergyPLAN, a deterministic hourly input–output model developed at Aalborg University [33] and widely used for energy-system analyses [34]. It provides an integrated representation of sector coupling across electricity, transport, heating/cooling, desalination, industry, and gas [20]. EnergyPLAN takes as inputs hourly demand, installed capacities, and renewable generation profiles (measured or weather-derived), together with techno-economic parameters and technology specifications spanning conventional plants (PPs), RES, storage, and alternative-fuel options (*e.g.*, biogas, hydrogen, electrofuels, WtE). The model outputs sector-resolved hourly and annual balances, including fuel use, electricity imports/exports, and CO_2 emissions, and can emulate various regulation strategies and aggregated economic indicators. Owing to its computational efficiency [20], EnergyPLAN is well-suited for large scenario screening. However, it lacks a native optimiser. To address this limitation, a dedicated MATLAB-based toolbox for EnergyPLAN was developed by Cabrera et al. [32], enabling integration of the modelling capabilities of EnergyPLAN with the elaboration potential of MATLAB. This toolbox has been successfully applied in previous studies , *e.g.* [22]. EnergyPLAN is available as freeware and can be downloaded directly from its official website [35]. Extensive documentation, including a detailed description of the model structure, mathematical foundations, and operating principles, is also provided online [36].

2.2. A posteriori techno-economic analysis

After the multi-objective optimisation, an a posteriori techno-economic assessment is performed for selected scenarios. This step does not affect the optimisation, but uses the resulting installed capacities and annual energy outputs to translate the technically feasible solutions into comparable economic metrics under consistent assumptions. The costing approach and key assumptions are summarised below. The economic assessment is based on annualised investment and operating costs. Capital expenditure (CAPEX) is annualised over the lifetime n using a discount rate $r = 3\%$ [37], while operational expenditure (OPEX) is modelled as fixed O&M costs expressed as a constant fraction of CAPEX. The annualised cost of each technology is calculated as:

$$CAPEX_{ann} = C_{inv} \cdot P_{inst} \cdot \frac{r(1+r)^n}{(1+r)^n - 1} \tag{1}$$

$$\mathrm{OPEX_{fix}} = f_{\mathrm{O\&M}} \cdot C_{\mathrm{inv}} \cdot P_{\mathrm{inst}} \tag{2}$$

$$\mathrm{Cost_{ann}} = \mathrm{CAPEX_{ann}} + \mathrm{OPEX_{fix}} \tag{3}$$

where C_{inv} is the specific investment cost [mln€/MW], P_{inst} the installed capacity [MW], $f_{\mathrm{O\&M}}$ the fixed O&M share of CAPEX per year, and n the system lifetime [years].

The average annualised cost of electricity from the generation mix is then obtained as:

$$\mathrm{Cost}^{\mathrm{mix}}_{\mathrm{energy}} = \frac{\sum_{i\in \mathrm{T}} \left(\mathrm{CAPEX}_{\mathrm{ann},i} + \mathrm{OPEX}_{\mathrm{fix},i}\right)}{\sum_{i\in \mathrm{RES}} E_{\mathrm{gen},i}} \tag{4}$$

where i identifies each technology in the portfolio, $E_{\mathrm{gen},i}$ is the annual useful generation [MWh/year], and T is the set of newly installed technologies. The resulting indicator, expressed in €/MWh, represents the LCOE of the entire mix. It provides a consistent metric to compare the economic competitiveness of different technology combinations and scenarios for electricity generation.

The net present value (NPV) is calculated as follows:

$$\mathrm{NPV}_0 = -\sum_{i\in \mathrm{T}} (C_{\mathrm{inv},i} \cdot P_{\mathrm{inst},i}) \tag{5}$$

while from the first year the NPV is calculated as:

$$\mathrm{NPV}_y = |\mathrm{NPV}_{y-1}| + \frac{S_y - \sum_{i\in \mathrm{T}} \mathrm{OPEX}_{\mathrm{fix},i}}{(1+r)^y}. \tag{6}$$

where NPV_y is the NPV (MEUR) for year y, S_t are the savings in year y (MEUR/year) (i.e. the avoided costs of conventional generation), and C_t is the total operational costs in year y (MEUR/year).

3. Energy system model

In the selected case study, the EnergyPLAN MATLAB tool is employed to explore the design space of potential ES configurations with RES integration. This scenario space exploration is performed using a genetic algorithm (GA)-based approach, which aims to solve a multi-objective optimisation problem by identifying a set of optimal solutions $\mathcal{S} \subset \mathbb{R}^{N_e}$, with N_e being the dimension of the design space $\mathcal{X} \subseteq \mathbb{R}^{N_e}$. Each solution is uniquely defined by the design vector $x \in \mathbb{R}^{N_e}$. Depending on the complexity of the modelled ES and the defined optimisation problem, the N_e components are represented as a combination of:

- the RES installed capacities, in this study onshore wind turbine (C_{WT}) solar PV (C_{PV}), and offshore wind turbine (C_{OWT})
- the battery energy storage system (BESS) installed capacity (C_{BESS})
- the interconnection cable size (C_{cbl}).

To support carbon-neutrality targets, CO_2 minimisation is set as the primary objective, while satisfying the annual electricity, heating, and cooling demands $\left(D_e, D_h, D_c\right)$ through their normalised hourly profiles $\{\hat{\mathbf{D}}_e, \hat{\mathbf{D}}_h, \hat{\mathbf{D}}_c\} \subset \mathbb{R}^{N_y}$, with N_y being the number of hours in the year. Site-specific renewable availability is represented in EnergyPLAN via normalised hourly production profiles for onshore wind, offshore wind, and PV, $\{\hat{\mathbf{P}}_{wind}, \hat{\mathbf{P}}_{owt}, \hat{\mathbf{P}}_{pv}\} \subset \mathbb{R}^{N_y}$. Here, $\hat{\mathbf{P}}_{wind}$ is obtained by normalising the power production data provided by Red Eléctrica de España (REE), the local transmission system operator (TSO) [38]. Due to the absence of hourly data for solar production, $\hat{\mathbf{P}}_{pv}$ is computed based on available solar irradiation data, assumed to be representative of PV generation. A more detailed representation of the solar radiation data in EnergyPLAN is considered beyond the scope of this work. The solar irradiation data were obtained from [39].

The annual energy production (AEP) from each ith RES is calculated over N_y hourly time steps as:

$$\mathrm{AEP}_{\mathrm{RES}_i} = \sum_{j=1}^{N_y} C_{\mathrm{RES}_i} \cdot \hat{P}_{j,\mathrm{RES}_i}. \tag{7}$$

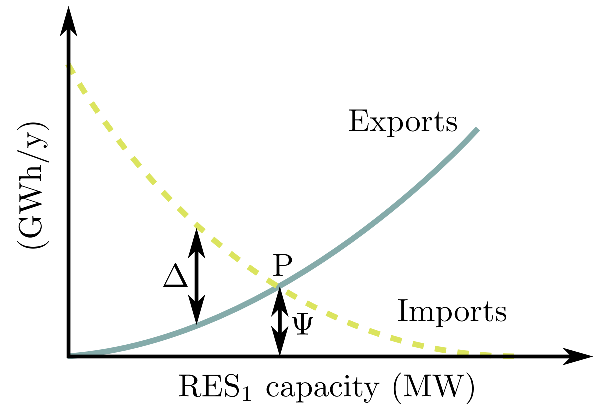


Fig. 2. Graphical representation of the objective functions.

Therefore, installed RES capacities are interpreted as effective values within the model. Total CO_2 emissions account for PP generation, transport fuel use (F_t), and natural gas (NG) demand (N_{gas}). BESS interaction is represented through maximum charge/discharge power (S_{ch}, S_{dis}) and charge/discharge efficiencies (η_{ch}, η_{dis}).

In isolated systems, fully replacing conventional PPs (with capacity C_{PP}, efficiency η_{PP}) via RES oversizing is typically impractical due to their variability and limited dispatchability. Accordingly, RES overproduction (excess generation relative to demand) is used as a proxy for oversizing and is minimised alongside PP output. To avoid storage oversizing, a third objective is introduced via the storage exploitation index η_{BESS}, defined as the ratio between the discharged energy (E_{dis}) and the total ideally dischargeable energy over the year (E^0_{dis}):

$$\eta_{BESS} = \frac{E_{dis}}{E^0_{dis}}. \tag{8}$$

Table 2 gives all the variables involved in the EnergyPLAN simulation.

4. Optimisation problem formulation

In general, a multi-objective optimisation problem can be formalised as:

$$\min_{\mathbf{x}\in\mathcal{X}} \mathbf{f}(\mathbf{x}), \tag{9}$$

subject to:

$$\mathbf{g}(\mathbf{x}) \le 0, \quad \mathbf{h}(\mathbf{x}) = 0, \tag{10}$$

where $\mathbf{x}$ represents the design variable vector, $\mathcal{X}$ is the design space, and $\mathbf{f}(\mathbf{x}) \in \mathbb{R}^{N_f}$ is the objective function vector, with $\mathbf{g}(\mathbf{x})$ and $\mathbf{h}(\mathbf{x})$ representing the inequality and equality constraint vectors, respectively.

As stated in Section 3, CO_2 minimisation is the primary objective. However, technical and economic constraints discourage eliminating PPs solely through excessive RES deployment. Therefore, RES overproduction is used as an oversizing proxy and is minimised alongside PP production.

To capture oversizing and storage needs, the ideal storage concept proposed by Cabrera et al. [20] is adopted, which measures the difference between annual imports (PP electricity required under a given RES mix) and annual exports (hourly RES surplus). Reducing this difference (Δ in Fig. 2) toward zero implies that total RES generation matches annual demand, *i.e.* PPs could be eliminated under an ideal storage capacity Ψ. Although simplified, minimising this difference as the second objective (together with CO_2) implicitly discourages RES overproduction, allowing for better control of installed capacity. In Fig. 2, the bi-objective problem can be interpreted as driving point P toward

Table 2
Summary of the data employed in the EnergyPLAN simulation.

Parameter	Unit	Description
C_{PV}	(MW)	PV installed capacity
C_{WT}	(MW)	Onshore WT installed capacity
C_{OWT}	(MW)	Offshore WT installed capacity
C_{PP}	(MW)	Conventional PP installed capacity
C_{BESS}	(MW)	BESS installed capacity
C_{cbl}	(MW)	Island interconnection cable installed capacity
η_{PP}	(/)	PP conversion efficiency
N_{gas}	(GWh)	Natural gas (NG) demand
F_t	(GWh)	Fuel consumption for transport sector
D_e	(GWh)	Annual electricity demand
D_c	(GWh)	Annual cooling demand
D_h	(GWh)	Annual heating demand
$\hat{\mathbf{D}}_e$	(/)	Annual electricity demand normalised distribution
$\hat{\mathbf{D}}_c$	(/)	Annual cooling demand normalised distribution
$\hat{\mathbf{D}}_h$	(/)	Annual heating demand normalised distribution
$\hat{P}_{wind}$	(/)	Annual wind energy production normalised distribution
$\hat{P}_{owt}$	(/)	Annual offshore wind energy production normalised distribution
$\hat{P}_{pv}$	(/)	Annual solar energy production normalised distribution
S_{ch}	(kW)	Storage charge capacity
S_{dis}	(kW)	Storage discharge capacity
η_{ch}	(kW)	Storage charge efficiency
η_{dis}	(kW)	Storage discharge efficiency

0, thereby linking RES sizing to an idealised storage requirement. This formulation is preferred over direct overproduction minimisation to keep the objective interpretable in terms of storage needs. Accordingly, the optimisation problem is formulated as:

$$\min_{\mathbf{x}\in\mathcal{X}} \left(\mathrm{CO}_2, |\Delta(\mathrm{Imports}, \mathrm{Exports})|\right), \tag{11}$$

subject to:

$$\mathbf{X}_l \leq \mathbf{x} \leq \mathbf{X}_u, \tag{12}$$

where the goal is to minimise CO_2 emissions and the oversizing ($|\Delta(\mathrm{Import}, \mathrm{Export})|$) of RES installed capacities while ensuring that energy demand is met, considering the lower and upper boundaries constraint for the design vector elements, $\mathbf{X}_l$ and $\mathbf{X}_u$ respectively.

The optimisation is implemented in MATLAB using a GA, via `gamultiobj` function. Population size and number of generations follow MATLAB guidelines [40]. Standard selection, crossover, and mutation operators are used to promote exploration and mitigate premature convergence.

It is important to note that the optimisation problem is formulated in terms of technical performance indicators rather than as a single cost-minimisation linear programming/multi-integer linear programming (LP/MILP) problem. This choice reflects the primary objective of the study, namely to characterise technically feasible decarbonisation pathways and to quantify the role of different technologies (including capital-intensive options such as offshore wind) under realistic operating conditions. A purely cost-driven formulation would not only depend on possibly uncertain cost assumptions[1] and could penalise emerging technologies, while the adopted technical multi-objective set-up makes the trade-offs between deep decarbonisation, oversizing, storage needs and interconnection use explicit. Economic performance is then evaluated a posteriori in the techno-economic analysis, where representative Pareto-optimal portfolios are assessed in terms of investment requirements and cost of energy.

5. Case study: La Gomera

The Canary Islands have historically relied on petroleum imports due to their geographical isolation and lack of conventional resources. However, the archipelago benefits from abundant wind [43] and solar [44] potential, making it highly favourable for renewable energy deployment [45]. The seven main islands differ significantly in morphology: Fuerteventura and Lanzarote are flat, while others, such as La Gomera and El Hierro, are mountainous with low population densities, offering suitable grounds for comparative analyses [45]. El Hierro, in particular, has become a Spanish benchmark for decarbonisation [46], operating a wind-pumped hydro system able to cover most of its annual electricity demand [47].

Climatic conditions are shaped by the northeast trade winds and the Canary Current, resulting in high and stable wind and solar resources [50]. Another important aspect with respect to the present study is the availability of detailed energy reports published by the regional government and the TSO [51]. From an economic standpoint, the average LCOE in the archipelago is about 200.5 €/MWh [52], much higher than in mainland Spain, underlining the opportunity for cost-effective renewable integration [53].

5.1. La Gomera island: interconnection with Tenerife

La Gomera, selected as case study (Fig. 3), has long depended on imported diesel, mainly through the El Palmar thermal power plant in San Sebastián de la Gomera [52]. To address this, the *La Gomera 100% Sostenible* [54] project was launched in 2019, aiming to make the island 100% sustainable and a regional innovation hub for the energy transition. In 2023, five wind farms with a total capacity of 12 MW entered into operation, substantially increasing the renewable share [55].

A key component of the project is a planned subsea cable to Tenerife, scheduled for deployment in 2025 (Fig. 4). The 66 kV double-circuit line extends 36 km [56], reaching depths of over 1100 m, with substations in Chío (Tenerife) and El Palmar (La Gomera) [57].

The link is expected to enhance system robustness and enable La Gomera to exploit its full renewable potential, possibly achieving an annual surplus of green generation. This would reduce dependence on fossil fuels and improve energy security at the archipelago level [57]. It has additionally been reported that La Gomera has the largest area suitable for offshore RES deployment among the islands of the archipelago [58]. Such characteristics reinforce its relevance as a representative case study for the present analysis.

[1] *E.g.*, interested readers can refer to Moret et al. thesis [41] or works [42] for an in depth analysis of energy system planning optimisation under uncertainty.

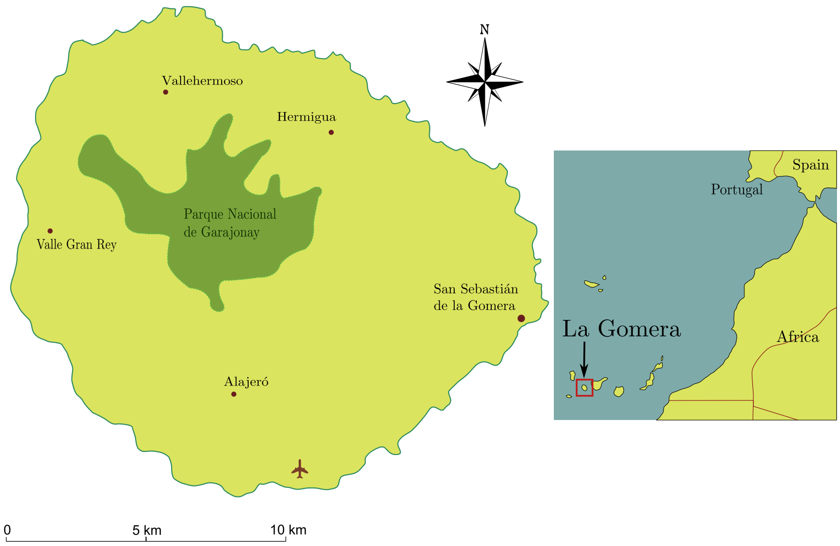


Fig. 3. Map of the island of La Gomera.
Source: Adapted from [48,49].

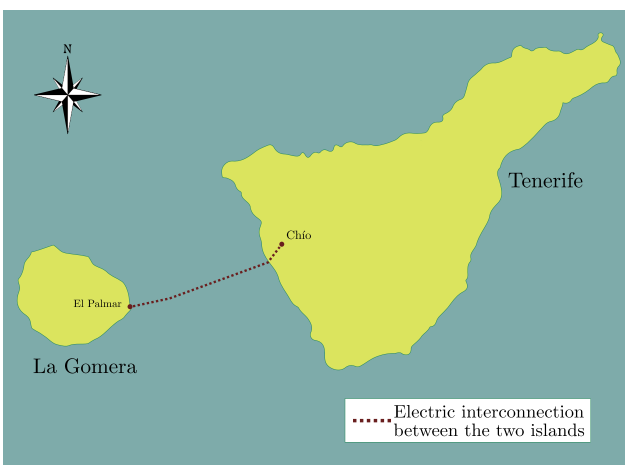


Fig. 4. Planned submarine interconnection La Gomera–Tenerife.
Source: [38]

5.2. Reference scenario: identification and validation

The reference scenario was defined from official statistics to ensure transparency, reproducibility, and consistency across sectors. The primary sources are the *Anuario Energético* (Energy Yearbook) published annually by the Canary Institute of Statistics (Instituto Canario de Estadistica-ISTAC) [59] and the regional government [52], complemented by hourly demand and generation data from the Spanish TSO [38]. When exogenous drivers were required (*e.g.* temperature or solar resource for shaping end use and PV profiles), established datasets, *i.e.* [39,60], were employed. This information was used to build an EnergyPLAN reference model of La Gomera and to derive coherent assumptions for the non-electric sectors.

Two electricity sector configurations were considered in line with the data horizon:

- *EnergyPLAN 2022 system (EP2022):* Energy demand covered almost entirely by the 21 MW El Palmar diesel PP, with a nominal efficiency of 37% (see Anuario [52] and data from local TSO [38]).
- *EnergyPLAN 2023/24 system (EP2023):* Addition of five wind turbines (WTs) (12 MW rated power) whose output was curtailed by the TSO to 2.23 MW, and commissioning of a new desalination unit in March 2024 [38]. This low RES penetration makes the island a suitable benchmark for investigating pathways towards a more sustainable ES, enabling both the provision of reference data and the exploration of potential transition strategies.

Accordingly, the first twelve months of wind turbine operation were selected as the reference period for the simulations (i.e. from April 1, 2023, to March 31, 2024). Other energy-using sectors were represented to preserve system-wide energy balance and emissions accounting:

- *Transport:* Dominated by fossil fuels (5.1 kt gasoline and 6.8 kt diesel annually), with electricity contributing only 0.13 GWh. Aviation and maritime consumptions were excluded from the model due to their international nature [52].
- *Natural gas (NG):* According to the 2022 annual report of the Canary Government, NG consumption on La Gomera amounted to 10.42 GWh/y. Since the official documents do not provide details on end-use applications, assumptions were introduced. Given the island's warm climate and the absence of district heating, household consumption was considered limited to cooking, while in the service and hotel sector a partial use for heating was assumed. Based on these considerations and data from from ISTAC [61] and University of La Laguna [62], the sectoral distribution of gas consumption was estimated. As no official report was available for 2023, the values reported for 2022 were extended to the reference timeframe.
- *Heating and cooling:* Sectoral demands derived from previously cited statistical shares and allocated to households (37.4 GWh in 2022) and hotels/services (34.1 GWh, including 5.4 GWh of NG). Seasonal allocation was shaped using temperature thresholds.
- *Water treatment:* La Gomera did not operate a desalination plant in 2022. However, a new facility became operational in March 2024, with its energy demand included in the overall electricity consumption. Wastewater treatment handles approximately 1.03 hm^3 per year, corresponding to an estimated 0.9 GWh/y, as derived from government data and comparative studies on other islands [63].

For the identified ES model, a system-level overview for 2023/24 is summarised in the Sankey diagram of Fig. 5. The Figure shows that,

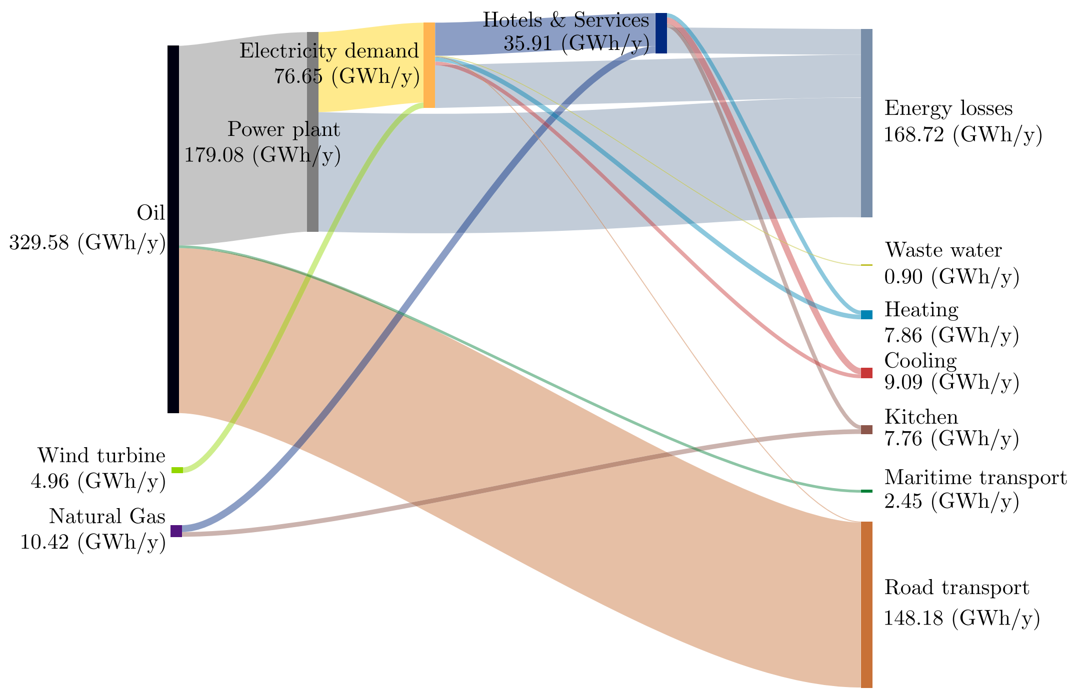


Fig. 5. La Gomera energy system of 2023/2024. The Sankey diagram has been built exploiting the data described in Section 5.2.

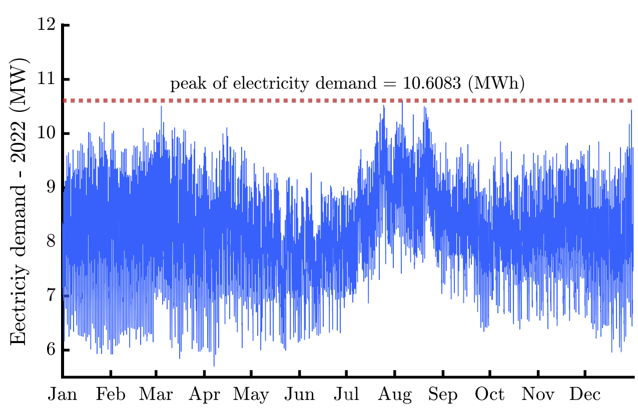


Fig. 6. La Gomera electricity demand in 2022.
Source: [38]

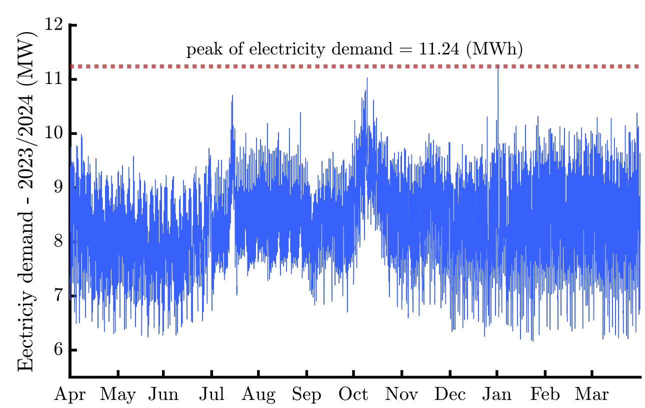


Fig. 7. La Gomera electricity demand April 2023–March 2024.
Source: [38]

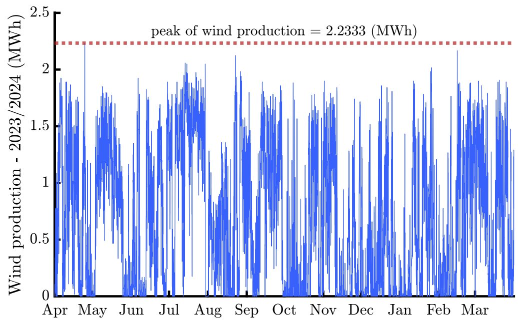
in the fossil-based reference case, losses represent a dominant energy sink.

The workflow proceeded as follows. EP2022 was first calibrated against El Palmar fuel consumption and system CO_2 emissions to validate NG and transport baselines, which were then carried over to 2023/24 when island-specific updates were unavailable. EP2023 subsequently incorporated observed wind production and TSO-reported curtailment. The hourly electricity demand profiles for 2022 and April 2023-March 2024 are shown in Figs. 6 and 7, while Fig. 8(a) reports the normalised wind operation curve used for validation. The late-summer increase in electricity demand reflects the actual measured profile reported by the Spanish TSO and is consistent with the combination of peak tourism activity and moderate cooling needs under the mild subtropical climate of the Canary Islands.

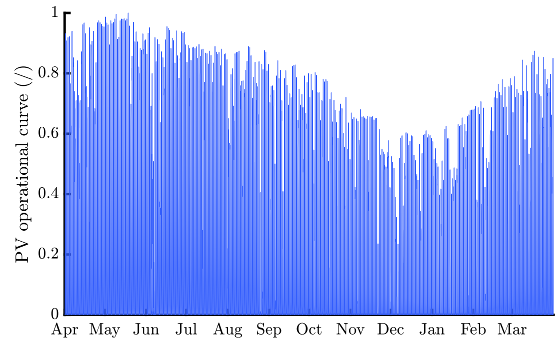
Table 3
CO_2 emissions and El Palmar power plant fuel consumption (F) validation for EP2022. Source: [52].

Variable	EP2022	Reference value	Error (%)
CO_2	92.9 kt	98.3 kt	5.5%
F	186.5 GWh/y	186.2 GWh/y	0.2%

Validation was performed separately for the two periods using El Palmar fuel consumption (F) and CO_2 emissions. For EP2022, reference values were taken from Anuario [52] and ISTAC [61], and the model reproduces both indicators with small deviations (Table 3), supporting the consistency of the NG and transport baselines used in EP2023. For EP2023, combining observed demand with wind production (including curtailment) from [38] yields mismatches below 3% for both F and eq-CO_2 (Table 4). Overall, the results confirm that the reference scenarios are suitable for the optimisation analyses that follow.



(a) La Gomera distribution curve of wind turbine operation: April 2023-March 2024. Source: [38]



(b) Reference PV operational curve for La Gomera between April 2023 - March 2024. Source: [39]

Fig. 8. La Gomera distribution curve of wind turbine operation and PV. *Source:* [38] and [39].

Table 4
CO_2 emissions and El Palmar power plant fuel consumption (F) validation for EP2023. Source: [38].

Variable	EP2023	Reference value	Error (%)
CO_2	888.6 kt_{eq}	882.3 kt_{eq}	0.71%
F	177.4 GWh/y	173.1 GWh/y	2.5%

Table 5
Optimisation design variables for Case 0.

Design parameter	Unit	Lower bound	Upper bound
PV installed capacity - C_{PV}	MW	0	100
WT installed capacity - C_{WT}	MW	12	100

Table 6
Optimisation design variables space for Case 1, (i.e. considering the interconnection cable).

Design parameter	Unit	Lower bound	Upper bound
PV installed capacity - C_{PV}	MW	0	250
WT installed capacity - C_{WT}	MW	12	250

6. Results

Following Section 2, the study evaluates the optimal RES portfolio for the validated La Gomera model through a stepwise increase in system complexity, leveraging EnergyPLAN's multi-sector representation to quantify how key system changes affect the optimal mix. For brevity, only selected optimisation outputs are shown in the main text. The complete set of plots is provided in Appendix.

6.1. Isolated La Gomera energy system

Case 0 optimises the isolated EP2023 model with PV and WTs only, each capped at 100 MW (Table 5), RES overproduction cannot be exploited without storage. Figs. 9–10 show the resulting Pareto set (red), trading CO_2 emissions (kt) against the mismatch objective $|\Delta(\text{Imports}, \text{Exports})|$.

Figs. 9 and 10 depict the same Pareto set using different colour metrics: total installed RES capacity and RES demand coverage, respectively. Relative to the nominal baseline (88.9 kt), all solutions yield substantial CO_2 reductions. However, transport and NG emissions (41.6 kt) impose a lower bound within the present scope. Accordingly, the optimisation primarily targets the PP-related electricity emissions (47.3 kt), leading to reductions of 63.4-82.2% for this component. Finally, smaller values of the mismatch proxy are preferable, as they indicate a more effective exploitation of the RES overproduction potential, even under idealised assumptions of ideal storage.

In Fig. 9, two areas were identified and highlighted as they contain potentially interesting sets of scenarios:

- *Area A*, located near the knee region of the Pareto frontier, includes scenarios where the reduction in CO_2 emissions is significant, while maintaining $|\Delta(\text{Imports}, \text{Exports})|$ below 100 GWh/year and the installed RES capacity around 80 MW. Beyond this value, increasing the RES capacity further may not represent a feasible solution for such a small ES.
- *Area B* represents another interesting set of solutions due to the considerably lower installed RES capacity, approximately half of the previous 80 MW, and consequently a lower $\Delta(\text{Imports}, \text{Exports})$, approaching zero, with emissions rising to 57–58 kt yet remaining substantially lower than the initial level of 88.8 kt.

6.2. Submarine cable interconnection to Tenerife

A 100 MW submarine interconnection between La Gomera and Tenerife is under development, primarily intended to export renewable electricity from La Gomera [57]. Accordingly, Case 1 updates the design space by representing the cable as a flexible demand (Table 6) and by increasing the RES upper bounds.[2] Exports are modelled as surplus RES generation that, on an hourly basis, exceeds both local demand and the cable's transmission capacity, while imports are computed as in Case 0 as the PP production required to meet internal demand.

Case 1 improves the performances by increasing RES demand coverage (Fig. 11), reducing surplus, and lowering CO_2 emissions, particularly for low $|\Delta(\text{Imports}, \text{Exports})|$ solutions. Reported emissions, however, refer to La Gomera only and do not credit the renewable exports that replace PP generation in Tenerife. This benefit is captured by the cable exploitation metric in Fig. 12, defined as the annual transferred energy relative to the cable's maximum transferable potential. As expected, the optimal portfolios require higher total RES capacity than Case 0 (Appendix Fig. A.23).

6.3. Energy system reinforcement stages

EnergyPLAN's SES formulation enables cross-sector analyses by coupling electricity with other energy-intensive domains [20], allowing future system developments to be tested on the validated model. To preserve comparability, the optimisation framework and objectives are kept unchanged. Following the sequential approach adopted by Cabrera

[2] Increasing RES upper bounds may require additional spatial-feasibility analyses (*e.g.*, land availability and siting) that are beyond the scope of this study.

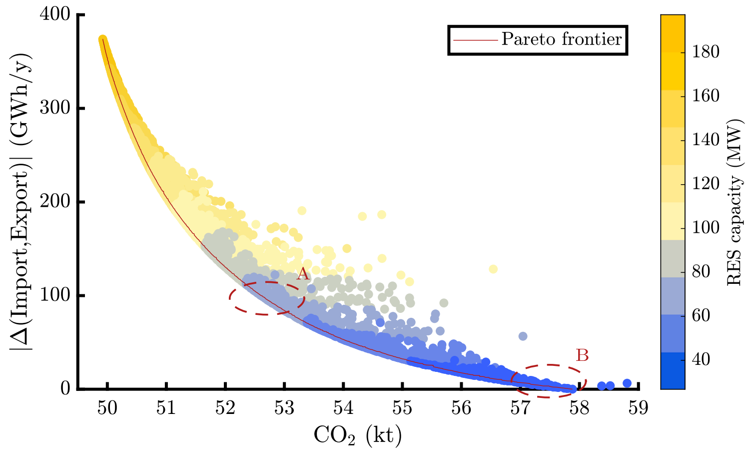


Fig. 9. Case 0 optimisation outcomes: different installed RES capacities and the resulting relative CO_2 emissions.

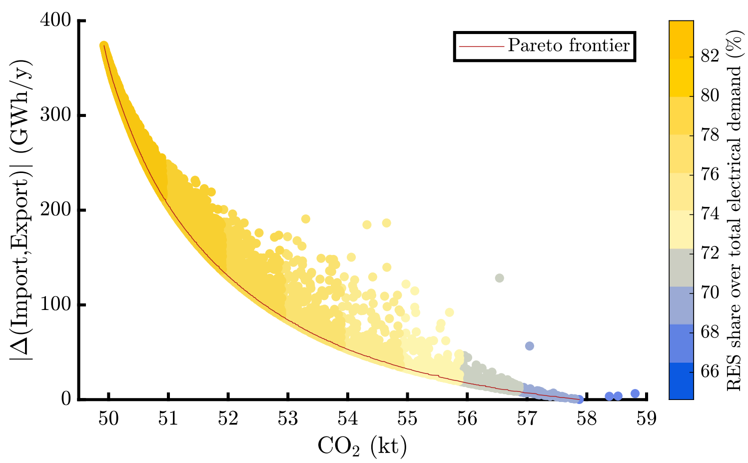


Fig. 10. Case 0 optimisation outcomes: RES participation in meeting demand, linking different share percentages to resulting CO_2 emissions.

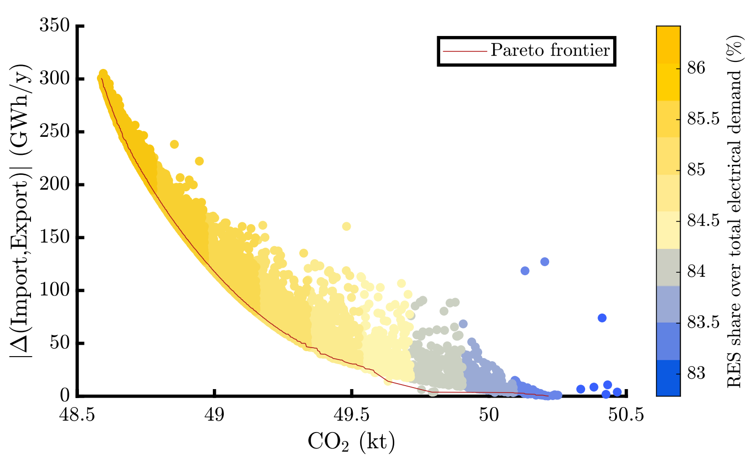


Fig. 11. Case 1 optimisation outcomes: RES participation in meeting demand, linking different share percentages to resulting CO_2 emissions.

et *al.* mentioned in Section 2, each step introduces a sector-specific enhancement that is then retained in subsequent stages, providing a consistent cross-sector perspective on the transition. Specifically, the stages introduced to reinforce the ES are:

1. Case 2, integration of a WtE plant to support generation and address waste management.
2. Case 3, deployment of BESS to mitigate RES variability.
3. Cases 4/5/6, electrification of 25%/50%/100% of the transport sector, anticipating the rise in electricity demand.

6.3.1. Waste management

Waste management on islands is limited by space and logistics constraints. The Canary Islands face significant difficulties in waste

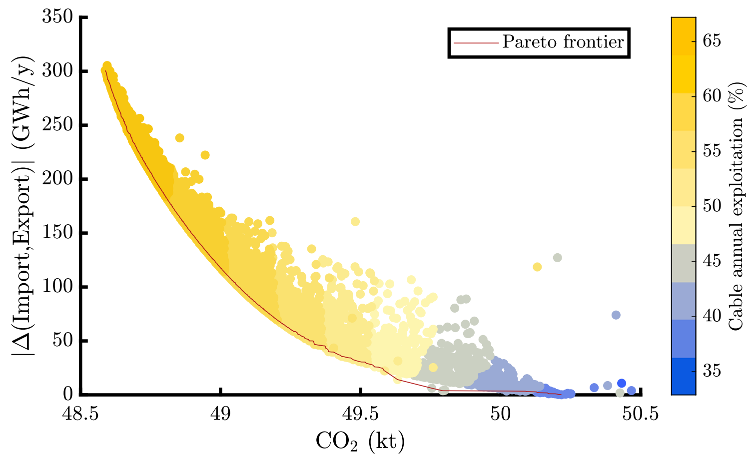


Fig. 12. Case 1 optimisation outcomes: cable utilisation in % of its total potential in terms of the amount of transferable electricity in one year.

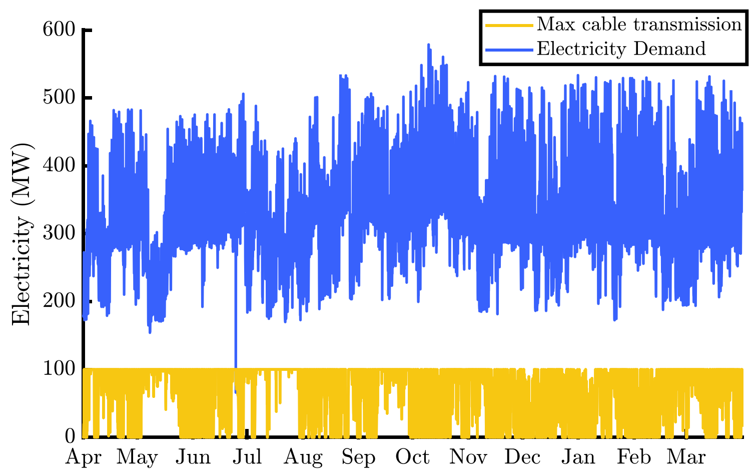


Fig. 13. Hourly maximum cable transmission from the 100 MW submarine cable (in yellow) compared with the electricity produced from fossil fuels (in blue, seen as a demand from La Gomera) in Tenerife for the EP2023 time horizon.
Source: [38]

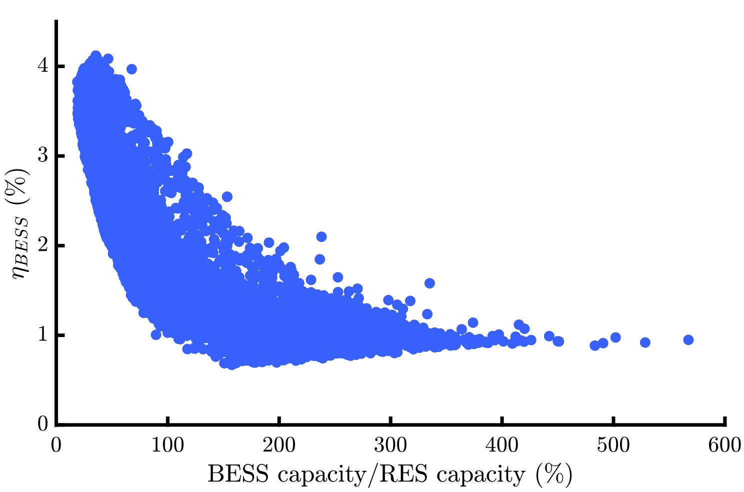


Fig. 14. Case 5: ratio between installed RES and BESS capacity plotted with respect to η_{BESS}.

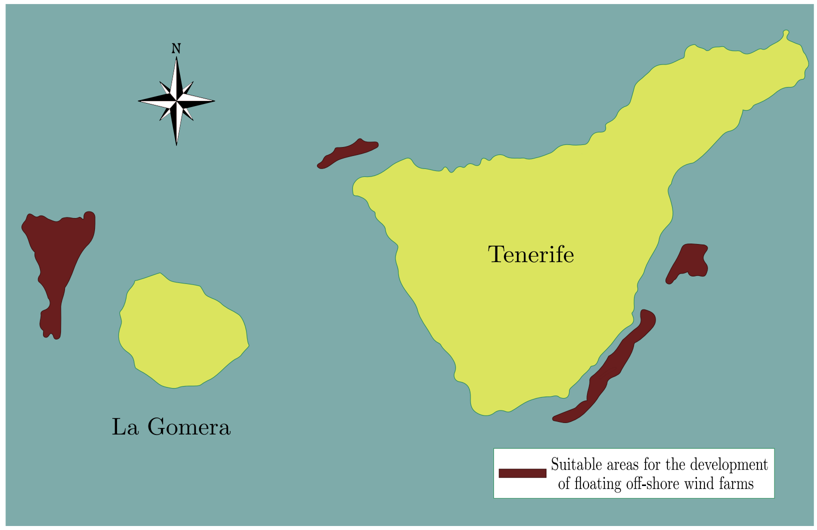


Fig. 15. Suitable sites in Tenerife and La Gomera for offshore wind farms.
Source: adapted from Yáñez-Rosales et al. [58].

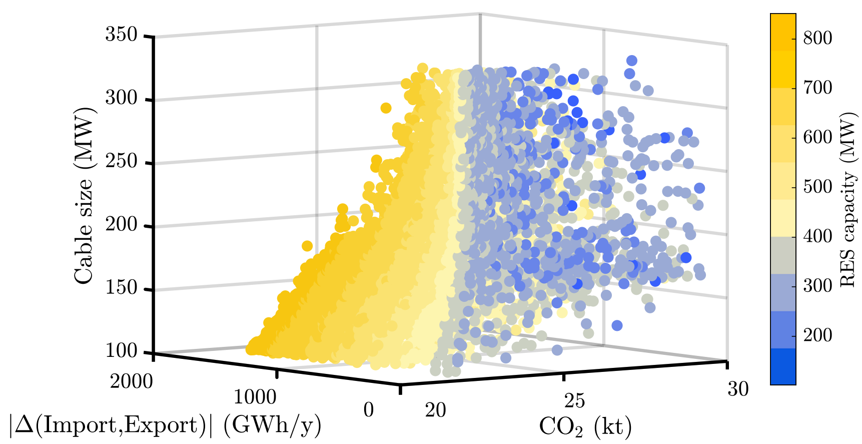


Fig. 16. Case 7 optimisation outcomes: relation between cable size in different scenarios and installed RES capacity.

disposal, further exacerbated by the impact of tourism. Currently, most waste is managed through landfilling, with only a small fraction being selectively collected, which remains below the national Spanish average [64]. Given its potential system value, the waste sector is considered here as a stabilising energy source in high-RES configurations. However, the integration of a WtE plant in the model requires several assumptions, which, while limiting, provide a preliminary understanding of how such a facility could interact with the ES under study. Statistical data and preliminary assessments of waste production in La Gomera [65] allowed an estimation of annual waste generation, corrected for seasonal fluctuations due to tourism on the basis of the 2023 resident population, yielding a raw energy potential of about 64.22 GWh/year [66].

A gasification-based WtE configuration is assumed, converting waste to syngas and generating electricity via an internal combustion engine. Reference efficiencies of 78% (gasification) and 25% net electric output are adopted [67]. The latter represents the overall net electrical efficiency of the full conversion chain and is consistent with state-of-the-art values reported by Panepinto et al. [67] for municipal solid waste plants (up to ∼22%–25%) [67]. Accordingly, the 25% efficiency is a realistic yet conservative assumption to avoid overstating the WtE contribution. CO_2 emissions from the WtE unit are included in the model, although a detailed characterisation is left for future work. Depending on the fossil fraction and composition of the waste, the specific CO_2 and air-pollutant emissions of a WtE plant can be comparable to those of oil- or gas-fired thermal generation. In this regard, studies highlight the potential of coupling WtE plants with carbon capture and storage technologies [68], with complementary evidence and analyses reported [69]. The electricity production from waste provides a reasonably stable source of generation within the system. The outcomes for this stage are reported in the Appendix in Fig. A.24.

6.3.2. Storage deployment

Storage integration is essential to mitigate RES intermittency and support grid stability [70]. In the Canary Islands, El Hierro illustrates the system value of wind–hydro storage system [47], while La Gomera is moving toward distributed electrochemical solutions [71], including batteries coupled to the WTs installed in 2023 (*e.g.*, [72]). In the model, a third objective (η_{BESS}) is introduced to align storage sizing with system needs and discourage oversizing. BESS capacity is allowed to vary from 0 to 500 MW (Table 7), assuming lithium-ion technology with a 2-hour charge and discharge rate [73] and 90% charge/discharge efficiencies (round-trip ≈80%), consistent with reported values [74].

Good performances were achieved with relatively low storage capacities. The main result of integrating a BESS is the potential for

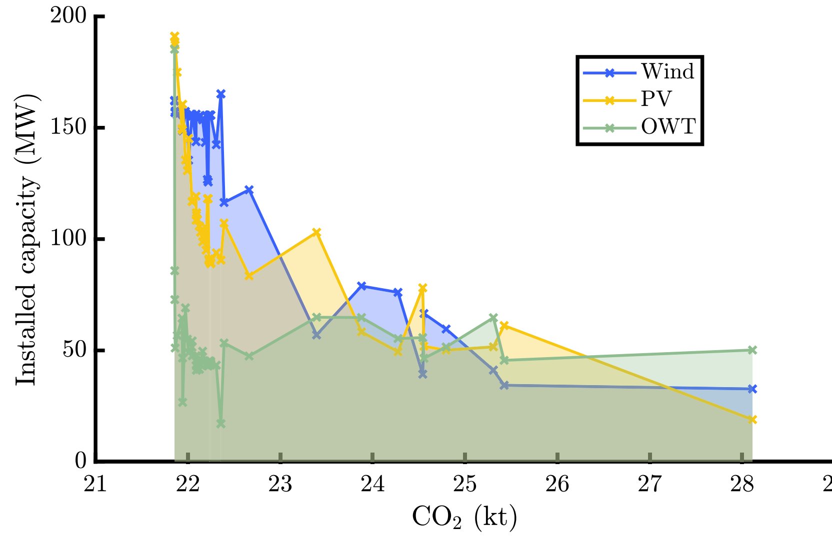
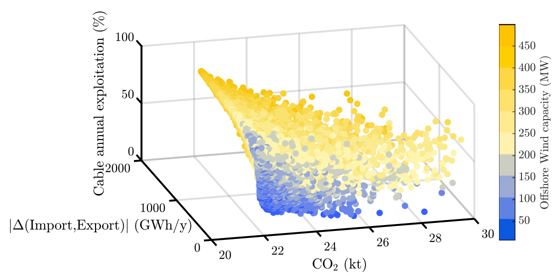
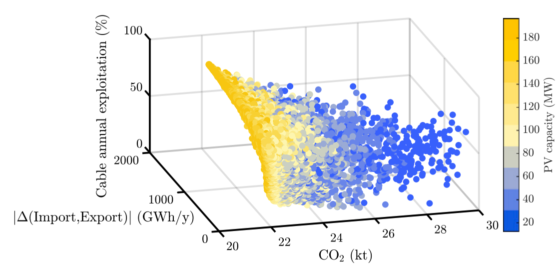


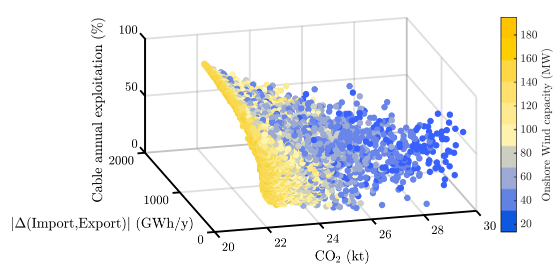
Fig. 17. Case 7 optimisation outcomes: capacities of PV, WT and OWT for Pareto surface points, ordered by CO_2 emissions.



(a) Case 7 optimisation outcomes: installed OWT capacity with respect to cable exploitation.



(b) Case 7 optimisation outcomes: installed PV capacity with respect to cable exploitation.



(c) Case 7 optimisation outcomes: installed WT capacity with respect to cable exploitation.

Fig. 18. Case 7 optimisation outcomes.

Table 7
Optimisation design variables space for Case 3 (*i.e.* the BESS-integrated case).

Design parameter	Unit	Lower bound	Upper bound
PV installed capacity - C_{PV}	MW	0	200
WT installed capacity - C_{WT}	MW	12	200
Storage size - C_{BESS}	MW	0	500

further emission reductions, even with the same or slightly reduced RES capacity compared to previous scenarios (see Figs. A.25(a) and A.25(b) in the Appendix). A BESS helps mitigate the volatility of RES, thus reducing the mismatch between demand and production, resulting in a lower PP share over the total electrical demand, as reported in Fig. A.25(c).

6.3.3. Transport electrification

As a final reinforcement stage, EVs are introduced to support transport decarbonisation by shifting mobility demand from direct fuel combustion to electricity. Consistent with long-term transition projections [75], transport electrification can be particularly beneficial in island systems by reducing fossil-fuel imports [76] and increasing the utilisation of locally generated RES [22]. However, EV integration adds new demand profiles that require careful management. Uncontrolled charging can increase peaks, whereas smart charging and V2G strategies can improve balancing and reduce RES curtailment [22]. Here, transport electrification is assessed through three penetration levels (25%, 50%, 100%), consistent with regional targets [77], to quantify its impact on the La Gomera system and the resulting optimal RES mix. In the absence of island-specific utilisation data, the transport profile is adopted from Canary Islands studies (*e.g.*, [20]) (see Table 8).

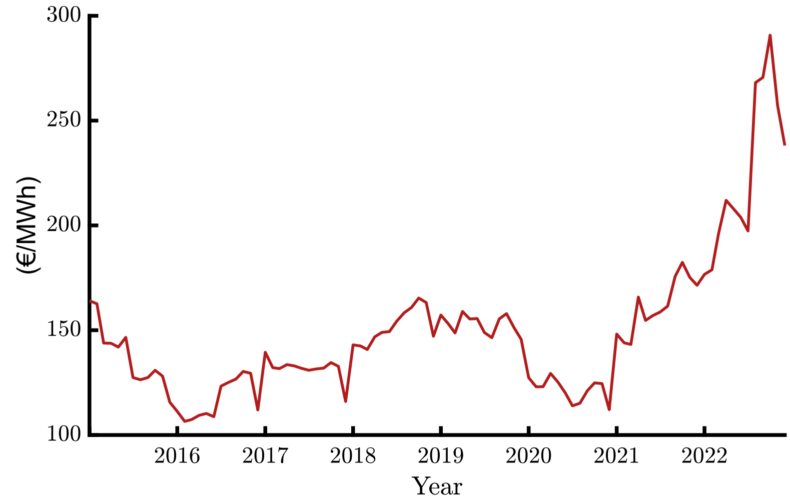


Fig. 19. Average cost of energy production in the Canary Archipelago.
Source: [52]

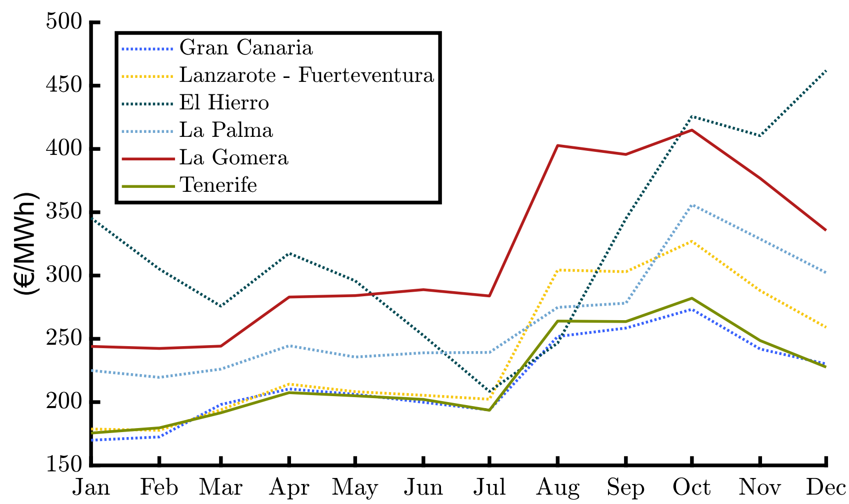


Fig. 20. Cost of energy production in the Canary Archipelago in 2022.
Source: [52]

Table 8
Optimisation design variables space explored during each of the three EV integration cases (i.e. for Cases 4/5/6).

Design parameter	Unit	Lower bound	Upper bound
PV installed capacity - C_{PV}	MW	0	200
WT installed capacity - C_{WT}	MW	12	200
Storage size - C_{BESS}	MW	0	500

At 25% EV penetration, PP generation decreases and cable utilisation improves (Figs. A.26(a) and A.26(b)), allowing more surplus energy to be absorbed and favouring higher wind shares (Fig. A.26(c)), with modest increases in total RES and BESS sizing (Fig. A.26(d)). At 50%, demand rises by ~35 GWh, with effects on PP share and cable utilisation (Figs. A.27(a), A.27(b)) less pronounced compared to the 25% case. The concentrated charging profile increases mismatches, leading to higher RES requirements (see Figs. A.27(c)) and wider variability in the PV–wind balance and BESS sizing (Figs. A.27(d) and A.27(e)), reflecting the need for greater system flexibility. Full electrification yields the largest emission reduction but nearly doubles electricity demand, requiring substantially higher RES (Figs. A.28(a)) and storage capacities (Figs. A.28(b)).

Overall, transport electrification supports emissions reduction and renewable integration, partly because EV charging can be shifted to low-demand hours, enabling valley filling [78]. Nevertheless, high penetration levels likely depends on the implementation of effective charging strategies, including coordinated charging and bidirectional schemes, to improve system efficiency.

6.4. Submarine cable optimisation via modelling of the tenerife energy demand

In 2022, RES supplied about 20% of Tenerife's electricity demand [52]. Thus far, the optimisation targets La Gomera, using the subsea link only to export surplus energy. Fig. 13 indicates that the planned 100 MW cable [57] can displace only part of Tenerife's fossil generation, motivating a sizing analysis. The following step therefore treats cable capacity as a design variable and evaluates the additional RES required on La Gomera together with Tenerife's effective absorption. Tenerife's fossil-based electricity is represented as an additional demand that can be met only via RES exports, constrained hourly by the interconnection capacity.

Building on the reinforced model, cable utilisation is introduced as a third objective to enhance the exploitation of the interconnection with

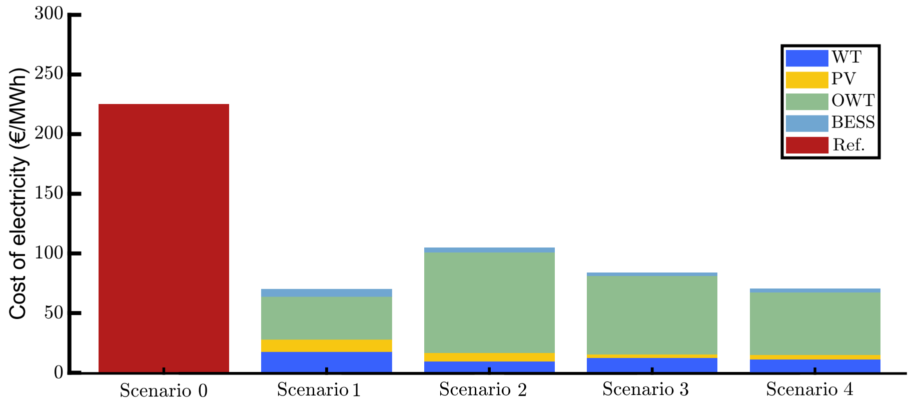


Fig. 21. Cost of energy resulting from the chosen scenarios and comparison with the 2022 price.
Source: [52]

Table 9
Optimisation design variables space for Case 7 (final optimisation round).

Design parameter	Unit	Lower bound	Upper bound
PV installed capacity - C_{PV}	MW	0	200
WT installed capacity - C_{WT}	MW	12	200
OWT installed capacity - C_{OWT}	MW	0	500
Cable size - C_{cbl}	MW	100	350

Tenerife, while retaining the objectives of minimising CO_2 emissions and the La Gomera mismatch proxy. For this final stage, EV penetration is fixed at 50% to represent a medium-term, ambitious target. To avoid a four-objective formulation, BESS capacity is prescribed. This isolates the interplay between RES deployment, cable utilisation, and emissions while maintaining a realistic storage contribution. The selected RES-to-BESS sizing is guided by the relationship between installed RES/BESS ratio and η_{BESS} (Fig. 14).

Since the maximum η_{BESS} is 4%, values around 3.5% are deemed satisfactory, corresponding to a BESS-to-RES capacity ratio of roughly 45%. In addition, given the island's limited land availability [66], offshore wind turbines (OWTs) are introduced to reduce reliance on land-intensive PV and WTs. OWTs offer higher wind speeds and capacity factors [79] and, with floating technologies advances, can be deployed in deep waters, unlocking high-resource sites with reduced visual impacts, albeit with higher capital costs.

For the Canary Islands, OWTs have been identified as a promising solution to meet growing low-carbon electricity needs. Yáñez-Rosales et al. [58] identified suitable sites and highlighted a high-potential area near La Gomera (see Fig. 15), although this zone is not currently allocated to offshore wind in maritime spatial planning [80]. For modelling, wind speeds were extracted at the selected coordinates [39] and combined with a Vestas V164-9.5 MW power curve [81], adjusted to a 100 m hub height, to derive an offshore generation profile. The final design space is reported in Table 9. Cable capacity is bounded below at 100 MW, consistent with the ongoing project, while the upper bound is set to the average between the peak and trough of Tenerife's demand curve to represent a reasonable transmission limit.

Emissions-mismatch trade-offs remain consistent with the reinforcement analyses, with a moderate mismatch increase as emissions approach their minimum. The main outcome is a marked rise in optimal RES capacity, enabled by treating cable size as a decision variable (Fig. 16).

Fig. 18(a) indicates that OWTs are preferentially deployed in high-utilisation solutions, where cable exploitation approaches saturation. Pareto points ordered by CO_2 (Fig. 17) show a roughly constant baseline OWT capacity, while WT and PV decrease as emissions rise. The different OWT/WT contribution at higher-emission solutions reflects the higher and more stable offshore resource. Extending the analysis beyond the Pareto set, Fig. 18 shows WTs increasing again at low emissions, reaching levels comparable to OWT, whereas PV remains systematically lower. Overall, these trends suggest that emission minimisation is primarily driven by wind resources, with PV playing a complementary role in shaping the generation mix to reduce mismatch. This supports the value of technology diversification to enhance system robustness and temporal alignment with demand.

6.5. Discussion

Across the optimisation rounds, CO_2 emissions decrease as additional sectors are included, consistent with SES literature evidence that sector coupling enlarges the feasible space for decarbonisation. In this case, residual transport and NG emissions initially impose a floor, but partial transport electrification shifts this constraint and makes near-zero emissions technically achievable, albeit requiring higher RES and storage capacities. Methodologically, the Pareto-based formulation is crucial to transparently expose the multi-objective trade-offs and to enable decision-oriented screening of the solution space, in line with prior studies (*e.g.*, Groppi et *al.* [15]; Ramos et *al.* [25]).

The Tenerife interconnection is a persistent system lever: treating the cable as a sink for surplus RES reduces $|\Delta(\text{Imports}, \text{Exports})|$ at any given emissions level, and cable exploitation remains high even under advanced decarbonisation, indicating that inter-island exchange remains central rather than marginal. This aligns with evidence that interconnection enlarges the balancing area and can reduce local overcapacity and backup needs. Accordingly, cable utilisation is a key complementary indicator for decision-making, alongside PP and RES shares and the optimisation objectives. Unlike stand-alone island studies, this work explicitly shows how interconnection introduction reshapes the optimal RES portfolio.

BESS deployment reduces mismatch and supports emission cuts, with most flexibility benefits achieved at moderate storage levels ($\eta_{BESS} \approx$ 3-4%) and diminishing returns beyond that range. This indicates that storage should be scaled progressively to complement, rather than precede, RES expansion and cable exploitation. Transport electrification increases demand but also introduces flexible load potential. Even without charging optimisation, higher EV penetration lowers PP reliance, maintains high cable utilisation, and favours larger wind deployment. These findings point to coordinated charging and V2G as key levers to further reduce curtailment, improve efficiency, and provide stability services, making EV policy an integral part of island RES planning.

The optimal RES mix shifts as additional options are enabled. OWTs enter the portfolio once cable capacity is optimised and deeper decarbonisation is pursued, while WTs remain a main contributor and

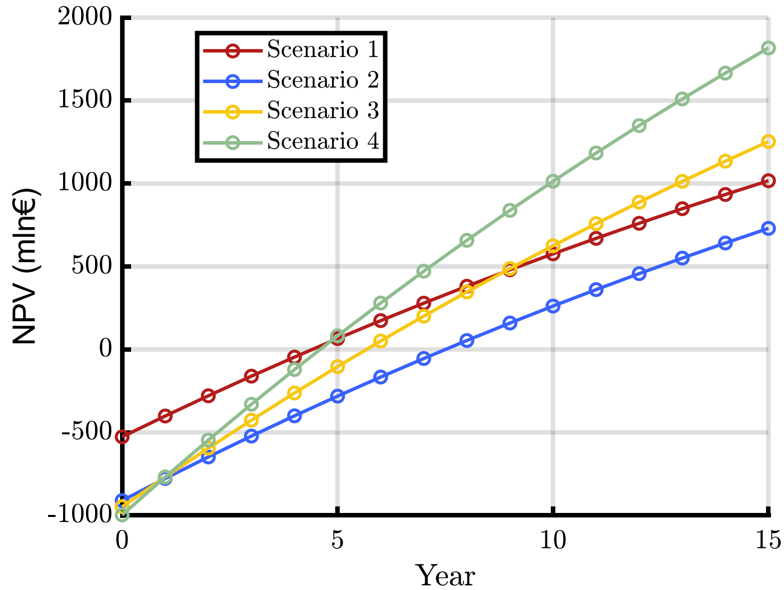


Fig. 22. NPV of the chosen scenarios to highlight the payback time.

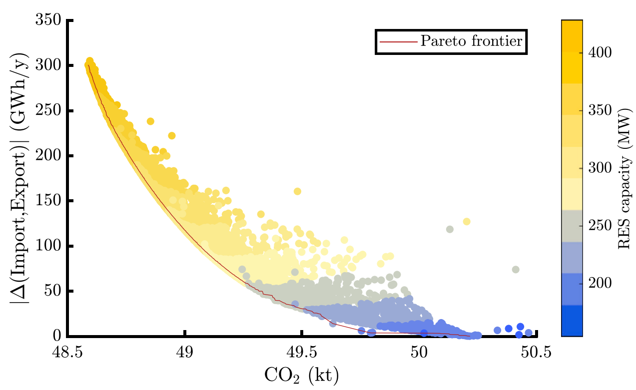


Fig. A.23. Case 1 optimisation outcomes: different installed RES capacities and resulting relative CO_2 emissions.

Table 10
Cost assumptions for the considered technologies, data from [22] and [74]..

Technology	Investment cost (MEUR/MW)	Lifetime (years)	Fixed O&M Cost (% of CAPEX/year)
WT	1.20	20	2.97
PV	0.50	20	0.60
OWT	4.50	25	2.10
BESS	0.30	15	2.00

Table 11
Summary of chosen scenarios.

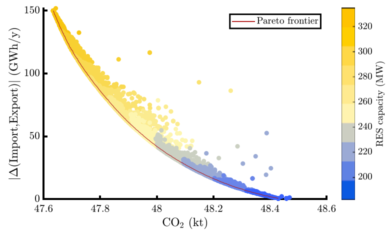
Characteristics	Scenario 1	Scenario 2	Scenario 3	Scenario 4
PV (MW)	175	137.5	78	123
Wind onshore (MW)	98	60	100	115
Wind offshore (MW)	63.5	165.5	170	170
Cable (MW)	100	100	150	250
BESS (MW)	120	85	80	110
PP share* (%)	0.27	1.3	1.45	0.43
Cable exploitation (%)	65.15	75.37	65.25	48.74
Δ Import/Export (GWh/y)	160.62	288.56	109.52	21.08
$CAPEX_{ann}$ (MEUR/year)	33.21	54.37	56.63	60.11
$OPEX_{fix}$ (MEUR/year)	10.74	18.70	20.34	21.19
$Cost^{mix}_{energy}$ (MEUR/year)	70.25	104.81	84.15	70.71

PV primarily supports profile shaping to limit mismatch. This diversification reflects complementary resource profiles and is particularly relevant under La Gomera's land constraints. Despite beeing capital-intensive, OWTs offer higher capacity factors and reduce land-use conflicts. Their growing role in the final stage suggests that larger exports to Tenerife become feasible when cable capacity exceeds the initial 100 MW, highlighting the need to align energy planning with maritime spatial planning for phased deployment. From a planning perspective, the results support a sequential pathway: initial PV and WT deployment with the 100 MW link, followed by moderate storage to mitigate mismatch, progressive transport electrification with smart charging, and ultimately eventual deployment of OWT enabled by cable expansion. Across stages, cable exploitation remains high and PP reliance declines.

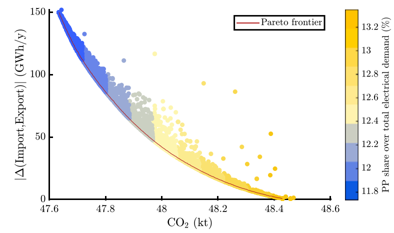
7. Techno-economic results

Among European countries, Spain stands out as a notable example of the successful implementation of specific energy policies and strategies [82]. Spain's peninsula overall energy mix benefits from large-scale wind and solar deployment (and nuclear), resulting in competitive electricity generation costs [83]. This differs markedly from the Canary Islands, where limited scale and lower RES shares contribute to substantially higher generation costs. Accordingly, the following techno-economic discussion benchmarks results against the archipelago-specific electricity prices reported in the Energy Yearbook [52], shown in Figs. 19 and 20, to quantify the potential cost reductions enabled by energy diversification and renewable transition.

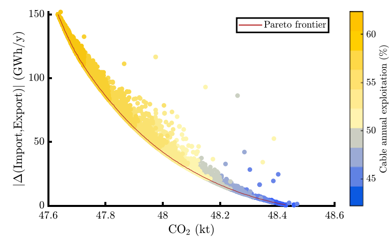
The investment costs and fixed O&M shares for onshore wind and PV, together with their associated lifetimes, are adopted from a previous study on the Canary Islands energy system [22]. Specific techno-economic data for offshore wind and BESS, which were not provided in [22], are taken from [74], which reports a lifetime of 25 years for offshore wind in island planning contexts. The resulting set of technology-dependent cost metrics used in this analysis is summarised in Table 10. The associated costs are the investment costs and fixed operation and maintenance (O&M) costs. However, since the WtE plant is only roughly designed (see Section 6.3.1), its costs are excluded from the generation costs. Similarly, the costs for the interconnection cable are omitted, as the planned infrastructure is assumed to be available. Thus, the analysis focuses solely on RES generation assets.



(a) Case 2 optimisation outcomes: different installed RES capacities and resulting relative CO_2 emissions.

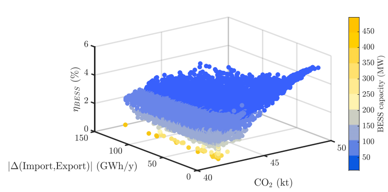


(b) Case 2 optimisation outcomes: PP participation in meeting demand, linking different share percentages to resulting CO_2 emissions.

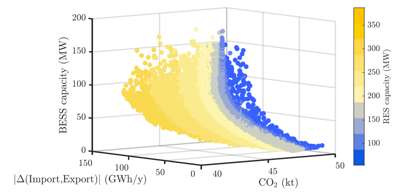


(c) Case 2 optimisation outcomes: cable utilization in % of its total potential in terms of the amount of transferable electricity in one year.

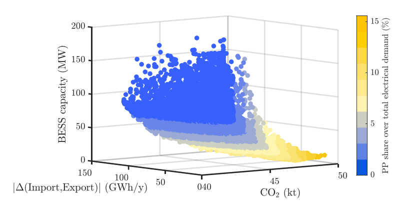
Fig. A.24. Case 2 optimisation outcomes.



(a) Case 3 optimisation outcomes: different installed BESS capacities and the resulting relative efficiency terms, CO_2 emissions and $|\Delta(\mathrm{Import}, \mathrm{Export})|$.



(b) Case 3 optimisation outcomes: different installed RES capacities and the resulting relative CO_2 emissions, $|\Delta(\mathrm{Import}, \mathrm{Export})|$ and installed BESS capacity effect on the system.



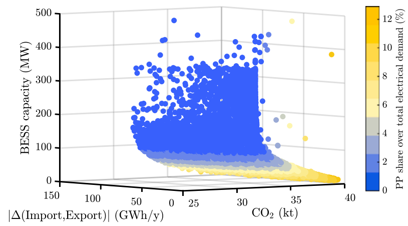
(c) Case 2 optimisation outcomes: cable utilization in % of its total potential in terms of the amount of transferable electricity in one year.

Fig. A.25. Case 3 optimisation outcomes.

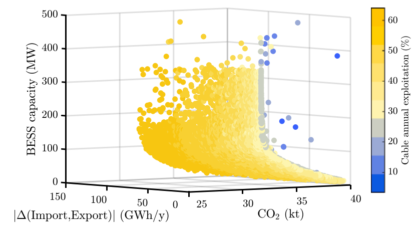
Four Case 7 configurations were selected by filtering cable capacity to 50 MW increments, consistent with the actual two 50 MW interconnector design. Two scenarios retain the nominal 100 MW sizing (the only solutions meeting this constraint while keeping transmission efficiency above 50%), and two additional scenarios adopt larger cable capacities to explore alternative layouts. The first pair is PV-dominated, whereas the latter pair was chosen to reflect a stronger wind contribution. Scenario features are summarised in Table 11, and the cost difference relative to the Canary Islands 2022 average electricity cost is shown in Fig. 21.

The onshore capacities reported in Table 11 imply a non-negligible land footprint. Indicative present-day installation densities can reach 125 MW/km^2 for PV plants (obtained considering a 25% PV modules efficiency and 50% of land utilisation) and 3 MW/km^2 for onshore wind [84]. The corresponding land requirement is estimated to be on the order of 5.7–10.7% of the overall La Gomera's 369 km^2, for the four selected scenarios. This estimate is intended as an order-of-magnitude planning indicator only, since steep orography, protected areas and competing land uses substantially reduce the land actually available. The reported capacities should therefore be interpreted as system-level targets whose feasibility must be verified through dedicated spatial planning.

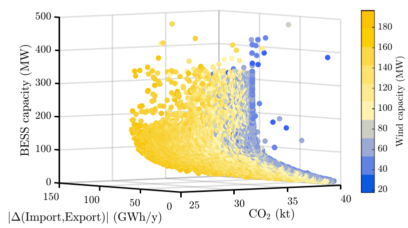
Fig. 22 reports the NPV over 1–15 years (aligned with the BESS lifetime) to indicate payback timing across scenarios. All configurations reach positive NPV within 5–10 years, supporting their economic viability. Scenarios with higher OWT penetration require larger upfront



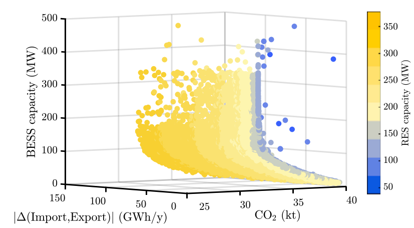
(a) Case 4 optimisation outcomes: 25% EV scenario: PP participation in meeting demand, linking different installed BESS capacities to resulting CO_2 emissions and $|\Delta(\text{Import}, \text{Export})|$ values.



(b) Case 4 optimisation outcomes: 25% EV scenario: Cable utilization in % of its total potential in terms of the amount of transferable electricity in one year.



(c) Case 4 optimisation outcomes: 25% EV scenario: different installed wind capacity scenarios and corresponding CO_2 emissions, effects of different installed BESS capacities and $|\Delta(\text{Import}, \text{Export})|$ values.



(d) Case 4 optimisation outcomes: 25% EV scenario: different installed RES capacities and the resulting relative CO_2 emissions, $|\Delta(\text{Import}, \text{Export})|$ and installed BESS capacity effect on the system.

Fig. A.26. Case 4 optimisation outcomes.

investments but deliver the highest NPV by year 15, reflecting greater cumulative savings. Overall, a RES-based La Gomera system combining storage and interconnection can lower generation costs relative to the current fossil-based supply while supporting decarbonisation objectives, highlighting the value of integrated clean-energy strategies for islands despite the simplifying assumptions.

8. Limitations

Despite the structured and internally consistent nature of the adopted methodology, several limitations must be acknowledged. The study does not explicitly address the spatial and regulatory constraints associated with land and marine space availability, which are fundamental for assessing the actual feasibility of large-scale renewable deployment. The limited share of effectively suitable onshore land on La Gomera (due to orography, protected areas and competing land uses) constitutes a key planning constraint that is not explicitly modelled in the present work. The onshore capacities in the selected scenarios should therefore be interpreted as system-level targets rather than as sited projects. A GIS-based suitability assessment (including land-use conflicts, rooftop/agrivoltaic PV potential, and the inclusion of spatial or regulatory constraints directly within the optimisation) is left for future work. In this regard, agrivoltaic solutions could help mitigate land-use conflicts while supporting renewable deployment [85]. Future work will assess this option and incorporate regulatory and land-use constraints directly into the optimisation (*e.g.* as spatial constraints or technology-specific capacity caps).

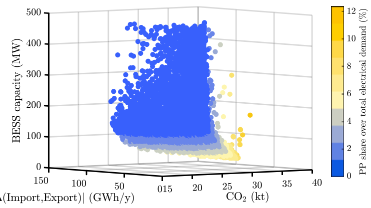
A further limitation concerns the simplified representation of the WtE plant. A dedicated analysis on WtE technology options, performance levels and local waste availability is therefore required to fully assess its role in the long-term system design and its implications for the techno-economic indicators. Similarly, while transport electrification has been shown in the analysed scenarios to enhance RES integration and reduce CO_2 emissions, EV demand is represented via defined penetration levels and fixed charging profiles. A more in-depth technical analysis, explicitly considering optimal charging strategies, infrastructure deployment and potential vehicle-to-grid services, is needed before drawing definitive conclusions on the contribution of the transport sector to system flexibility.

9. Conclusion

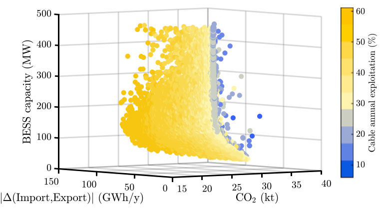
This study analysed the decarbonisation pathways for small and isolated energy systems, with La Gomera serving as a representative case study and focusing on its projected interconnection with Tenerife. The chosen approach involved optimisation of the RES portfolio. The modelling and techno-economic results confirm that high renewable energy penetration is technically feasible, provided that storage and interconnection infrastructures are adequately deployed. In particular, PV, onshore and offshore wind resources can effectively reduce fuel dependence and CO_2 emissions, although they require substantial upfront investments in BESS and grid reinforcements. These findings highlight the importance of adopting a multi-objective planning and optimisation framework that jointly considers technical reliability, economic performance, and environmental sustainability, rather than focusing exclusively on LCOE minimisation.

Consistent with the study hypothesis, the interconnection with Tenerife emerged as a critical enabler of system flexibility, facilitating both energy balancing and enhanced renewable utilisation. The results indicate that cable exploitation remains consistently high, demonstrating the strategic relevance of such infrastructure in achieving ambitious decarbonisation targets. Scenarios including inter-island connections show marked improvements in energy balancing, with the cable acting to leverage excess renewable generation from neighbouring islands. However, the associated capital costs must be carefully evaluated.

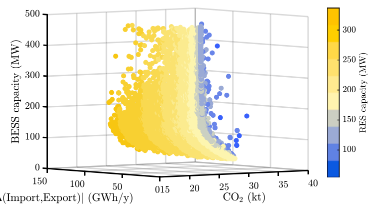
The electrification of transport showed synergistic effects, particularly when charging demand is coordinated with renewable generation availability, thereby supporting RES integration and limiting curtailment. Overall, the progressive integration of multiple sectors produced a clear downward trend in emissions, underscoring the value of systemic approaches aligned with the principles of SES [86].



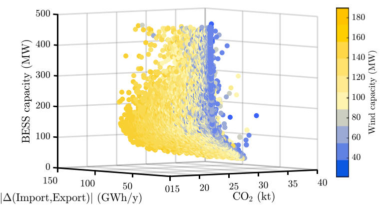
(a) Case 5 optimisation outcomes: 50% EV scenario: PP participation in meeting demand, linking different installed BESS capacities to resulting CO_2 emissions and $|\Delta(\text{Import}, \text{Export})|$ values.



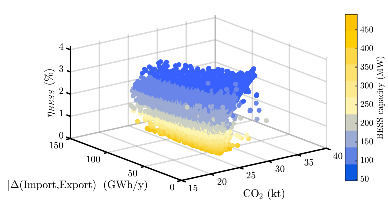
(b) Case 5 optimisation outcomes: 50% EV scenario: Cable utilization in % of its total potential in terms of the amount of transferable electricity in one year.



(c) Case 5 optimisation outcomes: 50% EV scenario: different installed RES capacities and the resulting relative CO_2 emissions, $|\Delta(\text{Import}, \text{Export})|$ and installed BESS capacity effect on the system.

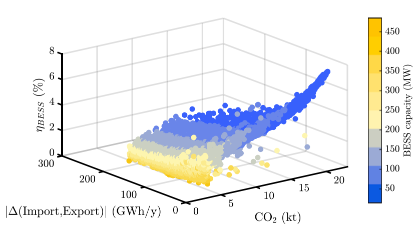


(d) Case 5 optimisation outcomes: 50% EV scenario: different installed wind capacity scenarios and corresponding CO_2 emissions, effects of different installed BESS capacities and $|\Delta(\text{Import}, \text{Export})|$ values.

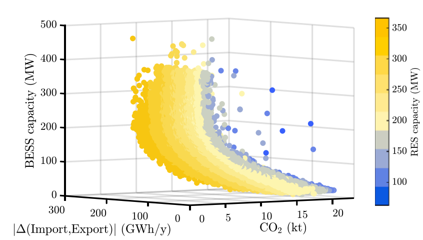


(e) Case 5 optimisation outcomes: 50% EV scenario: different installed BESS capacities and the resulting relative efficiency terms, CO_2 emissions and $|\Delta(\text{Import}, \text{Export})|$.

Fig. A.27. Case 5 optimisation outcomes.



(a) Case 6 optimisation outcomes: 100% EV scenario: different installed BESS capacities and the resulting relative efficiency terms, CO_2 emissions and $|\Delta(\text{Import}, \text{Export})|$.



(b) Case 6 optimisation outcomes: 100% EV scenario: different installed RES capacities and the resulting relative CO_2 emissions, $|\Delta(\text{Import}, \text{Export})|$ and installed BESS capacity effect on the system.

Fig. A.28. Case 6 optimisation outcomes.

From a broader perspective, the study underscores the value of optimal planning tools to guide energy transitions in island contexts. Although the scenarios do not represent a real-world optimum due to spatial, regulatory, and social constraints, they provide a consistent starting point for decision-makers. Finally, the methodological approach combining EnergyPLAN simulations, optimisation routines, and techno-economic assessments is formulated in a general and replicable way and could be applied to other insular contexts to support the design of their decarbonisation pathways. The shown economic viability, supported by favourable NPV and cost of energy outcomes, reinforces the relevance of integrated optimal planning in aligning local objectives with national and European decarbonisation targets.

9.1. Future works

From a methodological perspective, the present framework focuses on a multi-objective, technically oriented formulation and couples it with a separate techno-economic assessment. An interesting avenue for future work would be to reformulate the problem in a cost-minimisation LP/MILP framework, including indicators such as mismatch, storage exploitation and cable utilisation as additional constraints or objectives, and to compare the resulting portfolios with those identified here in both technical and economic terms. This would further clarify the extent to which cost-optimal solutions align with, or diverge from, the technically attractive decarbonisation pathways highlighted in this study. Future research should therefore extend the present framework by integrating spatial planning criteria (*e.g.* [87]) and regulatory considerations into the optimisation process. A fuller assessment of EV penetration and charging strategies, as well as a dedicated evaluation of WtE solutions, would further improve the comprehensiveness of the planning strategy. A more detailed representation of the Tenerife energy system should additionally be developed and subsequently linked to the La Gomera model through an appropriate pipeline.

CRediT authorship contribution statement

Ilaria Iacono: Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Writing – review & editing. **Filippo Giorcelli:** Writing – review & editing, Writing – original draft, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Visualization. **Filippo Spertino:** Validation, Supervision, Funding acquisition, Conceptualization, Writing – review & editing. **Pedro Cabrera:** Writing – review & editing, Validation, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization, Data curation.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix. Optimisation outcomes

See Figs. A.23–A.28.

Data availability

Data will be made available on request.

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