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THE ROLE OF ELECTRICITY IN THE ENERGY TRANSITION

A multi-dimension and multi-scale approach

Giulia Crespi

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Supervisors
Prof. Ettore Francesco Bompard
Prof. Stefano Paolo Corgnati

Doctoral Examination Committee:
Prof. M. Invernizzi, Referee, Università degli Studi di Genova
Prof. J. Kurnitski, Referee, Tallin University of Technology
Prof. G. Chicco, Politecnico di Torino
Prof. E. Fabrizio, Politecnico di Torino
Dr. D. Siface, Ricerca sul Sistema Energetico - RSE S.p.A.

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Giulia Crespi
Turin, 2021

Summary

Nowadays, energy transition is an extremely felt theme. Current energy systems, mainly based on fossil fuels, are clearly not sustainable and their transformation towards the achievement of carbon neutrality has started, aiming to reduce carbon emissions in all economic sectors. The boost of the European Union towards this objective has been reinforced by the publication of the European Green Deal, which aims to transform Europe into an efficient, fair and zero-carbon society by 2050. The advocated energy system changeover is often linked to a wider deployment of renewable energy sources, which in turn goes hand-in-hand with an expected higher electrification of final uses. These considerations are essential in the hereby PhD dissertation, which explores the role of electricity as a means for the energy transition, through diverse applicative studies, related to both demand- and supply-side perspectives. Furthermore, when dealing with energy transition phenomena, it is fundamental to keep in mind that energy systems are enclosed in intricate social, economic and political patterns and changes in their structure may have a strong impact also on society and economics. Purely techno-economic-based decisions do not represent the right approach for dealing with long-term transitions, neglecting various non-technical aspects, which conversely should play a not trivial role in the decision-making process. Long-term and low-carbon transitions need to be handled with a multi-disciplinary vision and to be supported by a strong policy framework, which in turn should be based on decision-making approaches able to integrate all the various facets of energy issues. Indeed, environmental concerns are pushing international and national governments to define policies to support the transformation of the current energy paradigm, identifying appropriate financial and market strategies to further boost and accelerate it.

These considerations represent the *fil rouge* of the research activities developed during the PhD, aiming to assess energy transition with a multi-disciplinary, multi-dimensional and multi-scale vision, with the scope of supporting and guiding the decision-making process at different scales and with diverse focuses, providing outcomes in the form of “usable knowledge”. In the light of the above, the PhD research pathway attempts to respond to the current challenge set to science, which should effectively provide evidences in support of the decision-making process, easily understandable by policy makers. To accomplish this, a general multi-layered

methodological approach is defined, aiming to provide a scientific basis for assisting the decision-making process in different contexts. The methodological framework is adopted at different scales of analysis, varying the level of knowledge, the research objectives and the targeted audience. In particular, the methodological approach is tailored depending on the analysed context, aiming to pinpoint the technologies and actors that are most likely to be core protagonists of the energy transition phenomena under investigation, to define tools to properly value and promote them and to identify the instruments that can be exploited to provide “usable knowledge” to the interested stakeholders. Specific applications at micro, meso and macro scales are presented and discussed, aiming to address some of the current challenges of the energy systems and the role of electricity in their transition, ranging from the increasing electrification of end-uses (focusing on the building sector) to the need for stronger policy support for the planning of large-scale electricity infrastructure.

Starting from the **micro scale**, in line with the vision of low-carbon and zero-energy buildings, great focus is put on the provision of all-electric buildings, which asks for a deep understanding of the possible technologies for providing heating and cooling services. Two applications are presented, both highlighting the role that energy efficient and sustainable HVAC systems play in the transition of the building sector. Attention is mainly devoted to electric solutions (i.e. heat pumps), thanks to their high energy efficiency and low environmental impact, if coupled with renewable energy sources. Both applications aim to value electric technologies, thanks to the development of ad-hoc analytical tools (i.e. simple or aggregate KPIs) for either market-oriented or policy-oriented purposes. The first application focuses on the valorization of the polyvalent heat pump technology, a promising solution for the decarbonization of the heating and cooling sector and for responding to new energy needs in buildings, highlighting the need to use a multi-perspective approach in the assessment and comparison of alternative technological solutions. This conclusive consideration is central in the second application at micro scale, in which proper graphical and analytical tools are defined, aiming to disclose information on the financial and environmental performances of widespread technologies for heating purposes for the residential sector, assessing the environmental benefits (or risks) that their adoption in individual buildings would guarantee (or generate). The analysis is developed to forecast and assess the reciprocal competitiveness of the technologies under investigation on the medium- (2030) and long-term (2050), to support the future energy planning of the building sector, and to study its variation according to different policy strategies.

Moreover, the latter analysis is extended to the **meso scale**, moving the lens from an individual technological assessment to a national perspective, studying possible pathways towards the decarbonization and electrification of the Italian residential sector. The meso scale analysis presents a technological-oriented study, which allows to identify the medium- and long-term electrification potential of the Italian residential building stock (mainly focusing on thermal uses), as well as to estimate the contribution of an electrification pathway to the overall reduction of energy consumptions and emissions. Thanks to the definition and use of appropriate aggregate metrics to drive the technological shifts within the national building stock, the application allows to address the impacts that possible future policy measures could have on the electrification potential of the thermal uses of residential buildings.

Finally, moving from demand-side to supply-side evaluations, attention is devoted to power system considerations. Specifically, the analysis at **macro scale** focuses on the assessment of a preliminary configuration of global grid, in line with the Global Energy Interconnection vision, permitting to transfer clean energy from RES-rich areas (i.e. Equatorial and Arctic regions) to the major load centres and exploring the associated challenges of transmission expansion planning at global and European scales. Different scenarios of electricity generation and consumption trends are compared, on the basis of regional- and global-scale metrics. Moreover, aiming to introduce non-technical factors in the planning of large-scale transmission planning and focusing on Europe, a second application is developed to combine the use of traditional power system modelling exercises (i.e. Optimal Power Flow) with multi-dimensional evaluation tools belonging to the operational research field (i.e. SWOT, multi-criteria decision analysis), to explore the capability of such tools to synthesize the energy complexity of large-scale transmission expansion planning and, thus, to guide the decision-making process in this field.

The elaboration of the PhD research is the result of activities carried out during the last years and supported by the external *stimuli* coming from international and national collaborations with experts in the field. The research pathway has allowed to identify a possible methodological approach to assess energy transition phenomena at different scales and with diverse energy system focuses and objectives. The scalability and multi-dimensionality of the research framework represents its main novel aspects, as well as the attention devoted to target the main stakeholders having the power to influence the investigated transition processes and to study the potential effects of appropriately defined policy strategies on stakeholders' decisions and expectations and on energy systems evolutions.

"Per due che come noi
non si son persi mai"

To Alberto

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Chapter 1

Setting the context

"[...] energy transitions are not inevitable; instead,
they depend on a series of actors and forces creating a new path.
Therefore, the complex interaction of the choices actors will make
and the forces that continue to be applied on markets,
along with a little serendipity, will influence the existence,
speed and nature of transitions to low carbon economies"
R. Fouquet, 2016 [1]

1.1 Complexity of energy transition

The awareness that energy is crucial for humankind is well established in people mindset. Energy is essential for guaranteeing economic development and social welfare, in the view of sustainability [2]. The importance of the theme has been acknowledged by international authorities [3] to the extent that the United Nations have recognized the access to affordable, sustainable and modern energy as a global priority for all citizens [2] [4, 5]. Sustainability generally refers to the need for economic growth to be compatible with socio-economic development and environmental safety [5, 6]. In this context, the theme of sustainable or clean energy transition is taking hold, due to the actual concerns on climate change, global warming and energy security the world needs to cope with [7].

In recent years, indeed, the topic of energy transition has powerfully entered within the technical, academic and political discussions. The term "transition" is usually used to describe a change or variation from a current to a future condition, and, according to this definition, it is clear that the energy transition terminology and phenomenon is not new. As reported in Ref. [3], energy transition can be considered as a permanent condition, due to the intrinsic transitioning behaviour of

[1] "Historical energy transitions: speed, prices and system transformation" [1]

[2] 7^{th} Sustainable Development Goal: "Affordable and clean energy" [4]

energy systems. However, according to recent literature, what mostly differentiates current energy transition from the earlier ones is the transitioning speed [3]. If the previous energy transitions (from primitive forms of energy to coal, from coal to liquid and gaseous hydrocarbons) can be considered as gradual processes, which took decades or even centuries to occur, in this case the current energy transition is strongly accelerated by the need to face the urgent global challenges [3]. Indeed, Grubler stated that the need for the future energy transition is justified by the non-sustainability of current energy systems according to social, economic and environmental perspectives, and this urgency is asking policy makers and researchers to promptly act [8].

Even though a standard definition of energy transition does not exist in literature, it is possible to identify a common *fil rouge* among the different terminologies [9]. Based on an extensive literature review on the theme [10, 11, 12, 13], Sovacool has defined energy transition as "a change in an energy system, usually to a particular fuel source, technology, or prime mover" [9]; similar definitions are provided by Hirsh et al. [14] and Miller et al. [15], identifying energy transition with changes in how energy generation and consumption sources are used. According to O'Connor, energy transition is "a particularly significant set of changes to the patterns of energy use in a society, potentially affecting resources, carriers, converters, and services" [16]. Fouquet et al. posed the accent on economic aspects, defining energy transition as "the switch from an economic system dependent on one or a series of energy sources and technologies, to another" [17]. Finally, Smil stated that "the term energy transition is used most often to describe the change in the composition (structure) of primary energy supply, the gradual shift from a specific pattern of energy provision to a new state of an energy system" [18], even though according to Smil, in the past, energy transitions were mainly characterized by the addition of new resources in the energy system, rather than by the substitution of the existing ones, which is the main objective of the on-going energy transition [18]. Still, Araujo stated that energy transition is identified as "a shift in the nature or pattern of how energy is utilized within a system" [19]. In her work, the author puts attention on the fact that energy transition is associated to a change in energy systems regarding "fuel type, access, sourcing, delivery, reliability, or end use, as well with the overall orientation of the system" [19]. According to this definition, surely, energy system transformation can happen at any scale, from global to local [19], as also suggested by Smil, according to whom energy transition can be visible at different scales [18], even though with different perspectives and needs. Finally, in Ref. [20], energy transition is defined as a shift of the global energy mix, which might happen according to different reasons: i) new national priorities; ii) new technological advancements; and iii) public awareness and regulatory policies upon the climate change issues.

This latter definition moves the lens from a merely techno-economic description of energy transition to a wider perspective, involving political and social aspects.

Indeed, despite the key role that technologies play in the achievement of future energy transition, there is the need to surpass a purely technology-centred approach, since technological advancement is not enough [5, 21]. Lee et al., indeed, criticized these technology-centred definitions, mainly considering energy transition as a pure change of energy mix or technological solutions, but not giving the right weight to the interconnection of energy systems with socio-economic and political aspects [21]. Nevertheless, this consideration is crucial. Indeed, energy systems cannot be separated by socio-economic systems [5, 22], since it is clear that the on-going energy transition is affecting also the socio-economic sphere, having impacts, for instance, on new jobs creation, GDP increase, as well as on the improvement of human welfare and health benefits (see Figure 1.1) [5]. In other words, energy transitions represent international and national challenges of fair and sustainable management of costs, risks and benefits in both environmental and socio-economic terms [23].

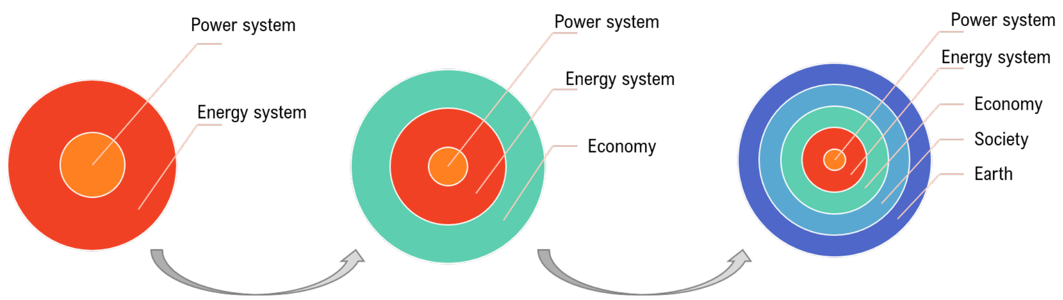


Figure 1.1: New perspective for the energy transition assessment: elaboration from Ref. [5].

These considerations are greatly supported by recent literature. As reported in Ref. [3], the modern energy transition is characterized and connected to socio-economic, ecological and geopolitical dimensions, since the required global transformation of current energy systems must urgently tackle the most significant energy challenges, among which energy poverty and inequality, climate change mitigation, energy security, economic development and global energy trade [3]. Similar considerations are reported by van Vuuren et al., identifying as challenging the increasing consumption levels at world level, the lack of universal energy access, the environmental risks (i.e. climate change, air pollution, and land and water systems impact), the energy security and the lack of long-term investment strategies in current energy policies [24]. Moreover, the global energy system is based on a "dynamic equilibrium", since it is characterized by growing demands, shifted between different countries and sectors, which asks for an environmental-friendly supply-demand matching [3]. Vijay Singh et al. well recognized the importance of these aspects in their definition of energy transition, which "includes a timely shift towards a more inclusive, sustainable, affordable, and secure energy system that provides solutions to the global energy related challenges" [3]. Finally, in Ref. [5], energy transition is defined as a "transformation of economies", rather than a purely energy system transformation, able to potentially bring benefits and opportunities, as well as to affect the current socio-economic dimension.

In order to identify the aspects embracing the energy transition concept, its main drivers and dimensions are depicted. According to Ref. [25], the main drivers of current energy transition can be summarized as: "political pressure, population growth and urbanization, improved economy of renewable energy sources (RES), growing demand for electricity and technological advancement". Similar considerations are reported in Ref. [20], in which also environmental and political elements are introduced, among which the rising of emissions and climate change issues and the geopolitical and national priorities. Bompard et al. explored the main drivers of the energy transition, identifying four main attributes: "energy efficiency, sustainability, energy security and economic affordability", which affect the entire energy chain and the different dimensions (or layers) of analysis (i.e. energy, economics, geopolitics, environment) [26].

Energy efficiency is defined as "the capability of ensuring the same services by lowering the quantity of energy used in the input", and, according to authors, the improvement of energy efficiency (mainly at end-use scale) could positively contribute to the decarbonization of energy systems, by resulting in a reduction of fossil-based energy use [26]. The sustainability sphere is mainly connected to availability of resources (fossil or non-fossil), RES penetration in the global energy mix, and associated environmental impacts, mainly in terms of greenhouse gas (GHG) and air pollutant emissions [26]. Moreover, according to the World Energy Council (WEC), sustainability is usually linked to the mitigation and reduction of energy-related environmental impacts, and thus it is generally connected to the use of clean energy resources, the efficiency of generation, transmission and distribution, and the assurance of air quality [27]. Energy affordability has been defined as the set of "strategies and actions to be implemented in order to promote the transition from fossil to renewable commodities in energy systems" [26]; generally speaking, this definition can be also enlarged to the wide political framework of taxation and subsidies adoption, that could be potentially used to penalize fossil-based technologies, rendering green and low-carbon solutions more competitive for consumers [26]. Finally, the theme of energy security appears a significant attribute of energy transition, and it has been greatly discussed in literature. In Ref. [26], energy security is defined as "the capability of guarantee that the quantities of energy commodities needed to fulfil the service demands are available, by local production or by import via energy corridors (pipelines, open sea routes, power lines, etc.)". A reduction of fossil fuels in the national energy mix (in turn linked with sustainability and decarbonization objectives) is strongly related to the energy security issue, especially for countries characterized by high energy imports dependency rates [26]. This topic was explored by the PhD candidate in Ref. [22], investigating the role that energy resources (both "green" and "black", representing RES and fossil resources, respectively) play in the socio-economic welfare of countries, recognizing energy as one of the four characteristics used to identify a "super-power", together with financial power, military force and technological capacity [22]. Due to the strategical role that energy sources play in modern economies, energy security is often identified in the national security [28]. Moreover, according to van Vuuren et al., energy security could be generically defined as the "uninterrupted provisioning of vital energy services", even though according to authors, some distinctions should be made between developed and developing countries [24]. For the former, indeed, the concept is more related to the dependency from imports and use of internally-produced sources, as well as to the reliability of energy infrastructure [24, 27], while the latter undoubtedly experience more vulnerabilities (e.g. "insufficient capacity, high-energy intensity, rapid growth in demand, supply and demand vulnerabilities overlap") [24]. The importance of energy security issues is well-reported in Ref. [29], identifying it as the main objective of national energy policies, together with other afore-mentioned energy transition attributes (e.g. energy affordability, energy efficiency, sustainability, etc.). Energy transition is strongly correlated to geopolitical aspects. Indeed, a transition towards a 100% RES-based energy mix may open the way to new geopolitical reconfigurations [5], power redistribution and sovereignty issues, which will potentially affect energy security [26]. Different consequences will be experienced by current importing and exporting countries (mainly of fossil fuels); the former, indeed, could benefit from higher levels of self-sufficiency, thanks to the exploitation of locally-produced renewable sources, while the latter will potentially face negative economic and political consequences due to the reduction of energy exports [29].

In line with the above, Vijay Singh et al. stated that "[energy transition] creates opportunities for business and society without compromising the balance of three key energy system performance categories which together make up the energy triangle. These three categories include economic development and growth, universal access to secure and reliable supply, and environmental sustainability" [3]. The cited energy triangle and the previous considerations are in line with the energy trilemma concept, which is usually associated to the energy transition challenge. The energy trilemma, as defined by WEC, is used to indicate the three main objectives of national energy systems, which recall what has been said so far: energy security, energy equity (meaning both affordability and accessibility to energy sources) and environmental sustainability [24, 27]. According to the energy trilemma vision, national energy goals could be achieved acting on five specific areas [27]: 1) energy supply transformation; 2) energy access advancement; 3) enablement of affordability at consumer level and competitiveness at industry level; 4) energy efficiency improvement and energy demand management; and 5) energy sector decarbonization. Clearly, WEC has recognized the key role that policy makers play in the achievement of a balanced energy trilemma and, generally, on a country energy performance [24, 27].

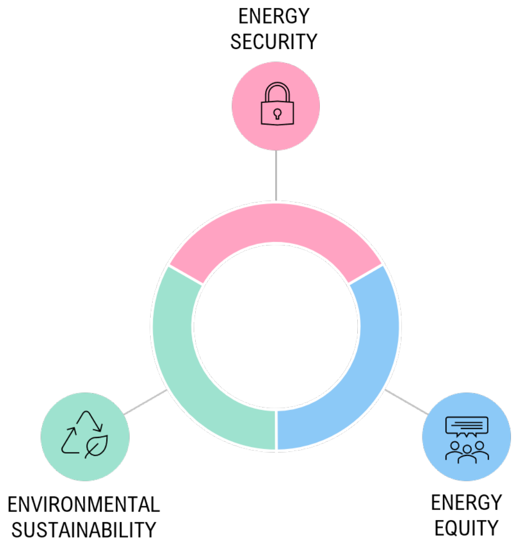


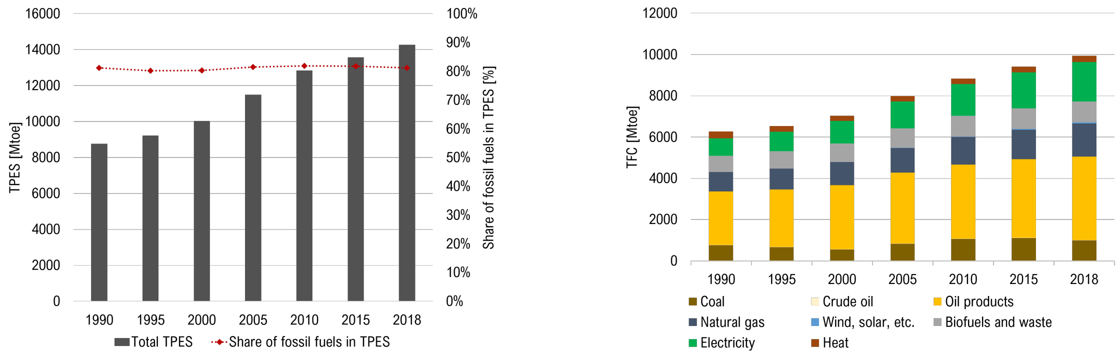
Figure 1.2: Energy trilemma: elaboration from Refs. [24, 27].

In the light of the above, it is clear that the energy transition phenomenon is by definition a multi-disciplinary and multi-dimensional issue (i.e. a "multi-layered process with multiple actors" [30, 31]), thus asking for proper inclusive methodological approaches for its assessment. According to Ref. [31], energy transition is characterized by the interaction between three main dimensions, which can change over time: i) tangible elements, among which "technology, infrastructure, market, production equipment, consumption patterns and distribution chains"; ii) actors with diverse needs and interests; and iii) regulations and policies. Similarly, according to Liu, technological advancements and energy policy regulations "mirror the combined effect of science and technology and government regulation on economy, energy and the environment" [32]. Indeed, on the one side, a technology-oriented perspective allows to achieve energy efficiency improvements and environmental savings; on the other side, socio-economic development, energy supply and consumers' behaviours must be regulated and guided through appropriate energy policy and regulation processes [32].

This point highlights that the desirable transition of the energy systems is certainly shaped by the political framework, which needs to be supported by science-based (or evidence-based) tools in order to identify the most effective strategies, able to integrate energy systems transformation with the wider socio-economic dimension, and thus to frame policies able to benefit from the synergies and interactions with the different dimensions, as well as to face actual challenges and conflicts [5]. According to Geels, energy transitions are necessarily a matter of "interactions between technology, policy/power/politics, economics/business/markets, and culture/discourse/public opinion" [33]. This complex and integrated framework asks for appropriate multi-layered approaches, in order to study the multi-dimensional facets of energy systems and their possible transitions [33]. In this sense, policy makers need to be guided and supported in identifying long-term strategies for energy planning at diverse scales, to set achievable targets, as well as to define proper policies and strategies able to push the market towards a low-carbon society [5]. Only if right and effective policies are put in place, with a cooperation between public and private stakeholders, as well as with a coordination at diverse territorial and institutional scales (from local, to regional, from national to international), the benefits of energy transition could surpass the existing challenges [5].

1.2 Role of electricity in the energy transition

The need for energy transition arises from the recognition of the non-sustainability of the current energy paradigm, still predominantly relying on fossil fuels, with negative drawbacks on environmental, economic and social spheres. As reported in Figure 1.3, at world level, the total primary energy supply (TPES) has steadily increased from 1990 to 2018 [34], while the share of fossil fuels (coal, natural gas and oil) in the total TPES has maintained almost stable, around 80%. The power sector is still mainly based on fossil fuels (the total share of coal, oil and gas in power generation was 68% in 2018 [34]), even though the share of RES has steadily increased from 15% in 1990 to 23% in 2018 [34]. Total final consumption (TFC) trends are depicted in Figure 1.3. Again, the share of non-renewable sources is significantly high, even though it is decreasing in time, thanks to a progressively wider RES deployment [34]. Another interesting figure regards the electricity share in TFC, which has slightly increased from 13% in 1990 to 19% in 2018, with a trend mostly dependent on the higher exploitation of electricity-based RES (e.g. wind, solar, hydro, etc.) [34]. Due to the prominent role of fossil-based sources in TPES and TFC, the impact of the energy sector in environmental terms is high, as well represented by the evolution of CO_2 emissions worldwide, which have increased of 63% from 1990 to 2018 [34]. Moreover, fossil fuels usage is connected to other issues, among which resource depletion, security of supply and related geopolitical tensions, or air pollution consequences on ecological systems and on people health. The transformation of supply and demand figures has been (and will further be) influenced by the international mitigation objectives over time, asking countries to increase attention and national efforts for assuring a GHG emissions reduction, in order to maintain global temperature rise below 1.5/2°C [35], and thus for pushing towards higher RES shares in TFC and TPES and stronger improvements of end-use level energy efficiency. At international level, the most impacting global commitment was achieved thanks to the Paris Agreement (Conference of Parties, COP21), signed in 2015 and entered into force in 2016 [35].

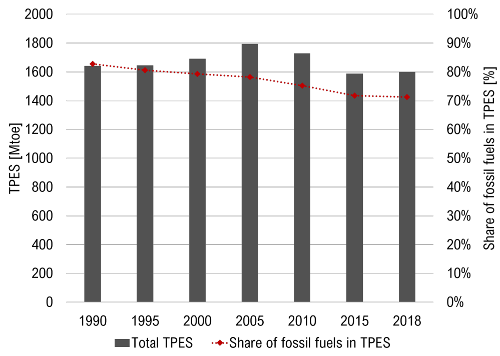


(a) TPES (b) TFC

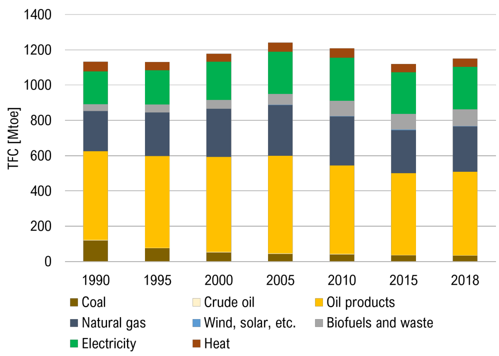
Figure 1.3: World energy figures [34]: (a) total primary energy supply (TPES); (b) total final consumption (TFC).

Coming to European statistics, a different situation emerges, also justified by the high commitment of European Union (EU) on climate change mitigation. Figure 1.4 shows the TPES evolution for EU-28 from 1990 to 2018 [34], with the indication of the percentage of fossil fuels share in the TPES (which is lower than the global value and has reduced over time) and the TFC trend by source. Also at EU scale, a higher share of electricity consumption is visible; electricity consumption has increased of 30% from 1990 to 2018, moving from a 16% to a 21% share in the total TFC [34]. From a sector perspective, in EU-28, in 2018, transport, residential and industrial sectors are the major energy consumers, representing 29%, 24% and 23% of the TFC, respectively [34]. When reporting EU energy situation, it is fundamental to remember that EU is characterized by a high import dependency rate; indeed, in 2018, a 58% dependency rate was measured in 2018, slightly increased with respect to 2000 value (56% rate) [36]. This is a medium value, averaging the situation of countries with dependency rate around 90% (e.g. Malta, Luxembourg and Cyprus), with those with values lower than 25% (e.g Romania, Denmark and Estonia). In 2018, Italy was characterized by a 76% dependency rate [36].

Thanks to the EU commitment in fighting climate change, CO_2 emissions has decreased of 22% from 1990 to 2018, coherently with the EU targets set for 2020 [34]. Parallelly, indeed, the share of RES in power generation has increased from 10% in 1990 to 31% in 2018, while the share of RES in TFC has reached 18.9% in 2018 [34]. Today, at European level, the existing targets are mainly based on the "2030 Climate & Energy Framework", published in 2014, and asking for at least: i) a 40% GHG emissions reduction (compared to 2005 levels); ii) a 32% share of RES in TFC; and iii) a 32.5% improvement of energy efficiency, by 2030 [37]. Moreover, the "Clean Energy for all Europeans Package", defined in the period 2016-2018, and the more recent "EU Green Deal", proposed in 2019, represented a stronger



(a) TPES



(b) TFC

Figure 1.4: EU-28 energy figures [34]: (a) total primary energy supply (TPES); (b) total final consumption (TFC).

push for the European policy context [38]; in particular, the publication of the "EU Green Deal" stressed the community aim of achieving carbon neutrality by 2050 (setting a higher target for 2030 in terms of GHG emissions reduction, with respect to the previous "2030 Climate & Energy Framework", and equal to 55% by 2030 [37, 38]) and it represents a desirable roadmap towards a more sustainable economy for EU, aiming to foster the investments in environmental-friendly technologies and the decarbonization of the energy sector. An attempted timeline of the most relevant EU climate and energy targets, directives and plans is depicted in Figure 1.5, in which also the main national energy and climate plans are identified, providing the example of the Italian situation, which will be touched in the PhD dissertation.

Given the above, the clean energy transition towards decarbonization is at the basis of international and national efforts in facing climate change consequences. The achievement of this energy transformation involves a considerable exploitation of renewable energy sources coupled with a shift towards electricity-fuelled final uses. The process of electrification of the energy sector, indeed, is identified as crucial in this transition pathway, being a possible solution to face current energy security, affordability and poverty issues, coping with the energy needs of individuals and communities. In line with this, the European Commission has identified electrification among the key trends that will most likely shape the future power systems [39] and the role of electrification in future energy systems has been broadly discussed in literature. In Bellocchi et al., the coupling of the electrification of energy sectors and the increasing penetration of RES is depicted as a key measure for decarbonizing energy systems [40]. Similarly, according to Ref. [32], two main decarbonization needs can be identified: "clean energy replacement" and "electric energy substitution". The first term is used to indicate the necessity to progressively transition from an energy system based on fossil fuels (with RES-based energy as "a component") to a system based on RES (with fossils as "a component") [32];

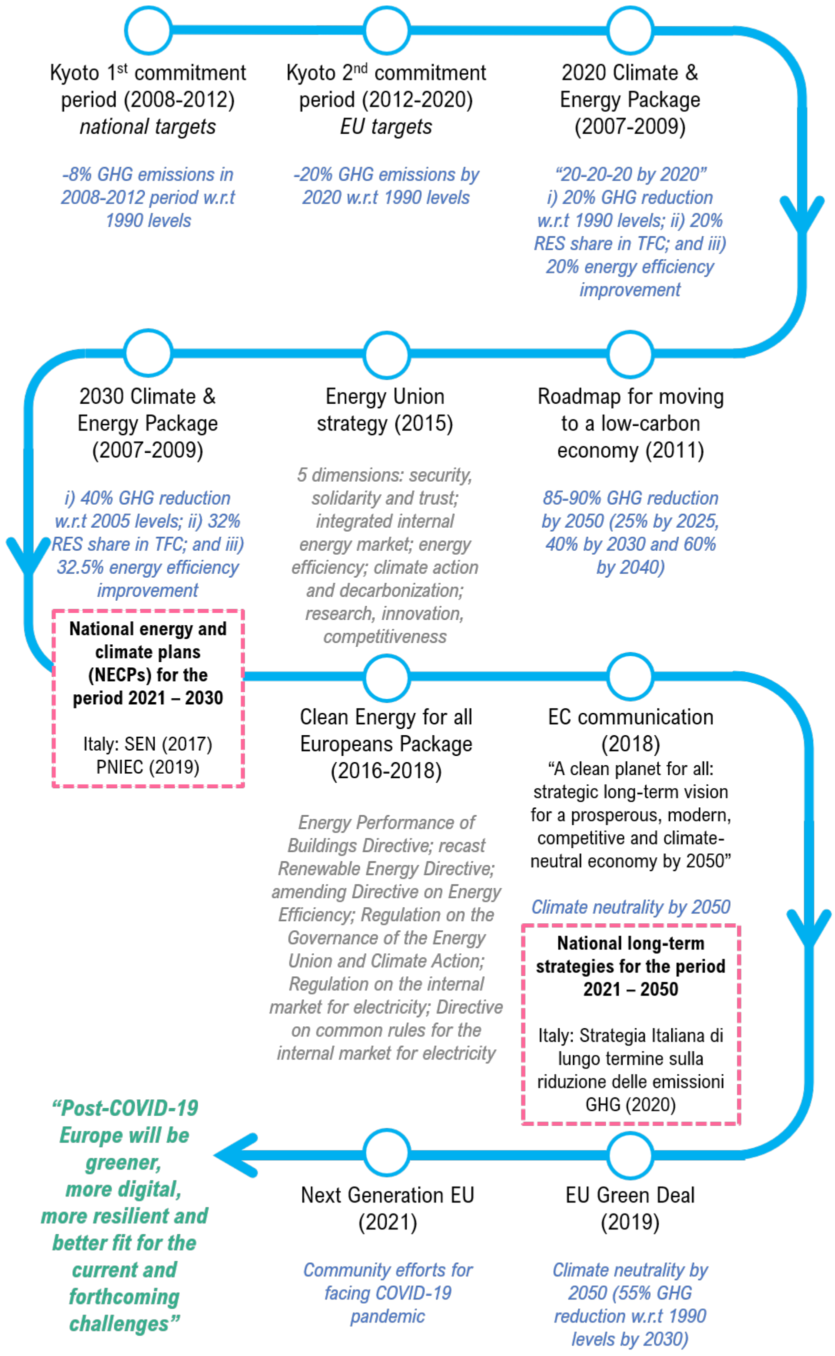


Figure 1.5: EU timeline: efforts for climate change mitigation [37].

this transformation would deal with the current issues of security of supply, environmental protection and economic development [32]. The second term is used to indicate the increment of electricity share in final uses; this realization would have positive benefits in terms of energy efficiency improvement, clean development promotion, and environmental safety [32]. In line with this, the energy transition vision promoted by Liu is usually recalled as a “two-replacement (or two-substitution) pathway” [32], integrating RES penetration and end-uses electrification.

According to Ref. [5], a RES-based paradigm surely represents an essential point of all new long-term scenarios, which recognize renewables, energy efficiency and electrification as the main pillars to achieve significant energy-related GHG emissions reductions in the medium- and long-term (in line with international and national targets). Specifically, RES integration is intended as the exploitation of renewable sources in the power sector (e.g. wind, solar PV, etc.) and in end-use applications (e.g. geothermal, bioenergy, solar thermal, etc.); energy efficiency comprehends all the efficiency measures undertaken in building, industry and transport sectors (e.g. insulation of buildings, substitution of inefficient appliances and energy systems, etc.); while electrification is used to indicate the shift of end-use energy consumptions (mainly transport and building sectors) to electricity [5]. This latter point has been discussed also by Bellocchi et al., who reported how the electrification of final uses mainly targets the transportation and heating sectors, due to their still high dependence on fossil fuels [40].

Clearly, a RES-based energy transition will pose challenges to the entire energy chain, from consumption, to distribution, to generation. Indeed, despite the potential benefits associated to a higher electrification of final uses (especially when coupled with RES-based electricity generation), this pathway will request a transformation of current power systems and demand-supply matching [5]. As reported in Ref. [41], in order to exploit the still untapped global renewable potential and to reach a higher electrification of end-uses, there is the need to find new solutions for electrical grids, devoting attention also to new market and regulation mechanisms and rules. In this framework, it is interesting to cite the work of Bompard et al., in which two possible and extreme paradigms for the future transition of the power sector are identified, which could potentially coexist in future configurations [26, 41]. On the one side, energy transition is usually linked to the concept of decentralization; indeed, the deployment of small-scale RES solutions will induce changes in the current power paradigm, transforming energy users from passive consumers to active prosumers, able to produce the energy they consume. This configuration is based on the diffusion of smart grids, able to accommodate the energy produced in decentralized systems [26]. On the other side, the second extreme energy paradigm is based on the installation of few and centralized RES generation facilities, concentrated in strategic areas with abundant clean resources, and connected through long-distance interconnectors to serve the main load centres [41]. Similar considerations are reported in Defuilley’s work, in which possible narratives (or trajectories) for future power sectors are described, ranging from a “re-arrangement” of current centralized paradigms (based on centralized renewables installations) to a complete “paradigm shift”, based on decentralized electricity production [42].

Besides the possible power systems configurations or trajectories, the impact of the energy transition on the whole sector is undoubted. According to Ref. [43], the power sector will double in size by 2050 and will be characterized by the addition of significant RES-based capacity (mainly wind and solar power). Due to the variability of these resources (both daily and seasonally), the power sector will request greater flexibility, which will be associated to diverse technologies and market solutions [43]. Moreover, regulatory frameworks and market restructuring will be required to face the underway evolution of the "consumer-producer relationship" [43]. In other words, the potential electricity-based transition, to occur, needs to be accompanied by energy storage improvements, higher flexibility, power grids interconnections, digitalization and decentralization of energy production [44]. Moreover, besides supply-side considerations, also demand side will be fundamental for the operation of a future electricity-based paradigm. To cite some, electric vehicle charging infrastructure, electric technologies in buildings and industries (i.e. heat pumps) and hydrogen production can be exploited and "adjusted" to provide flexibility to the grid [43]. A higher electrification of end-uses allows to maximize the benefits resulting from the combination of the improvement of energy efficiency at end-use level and a better energy demand management [45]. Indeed, as highlighted by Bompard et al., electricity is characterized by a higher conversion rate than fossil sources [41], and electricity-based technologies are usually characterized by higher energy efficiencies, especially in transport and building sectors [41].

The investigation of the role of electricity as a means for the energy transition is the overarching topic of this PhD dissertation, which aims to explore this issue from different perspectives and at different scales of deepening, in line with the so-called "electricity triangle" vision (outlined in Figure 1.6), which was firstly introduced in Ref. [46]. Specifically, the electricity triangle is deemed a feasible and suitable approach to energy transition [41]. Going into detail, the electricity triangle is described as an energy paradigm based on three pillars: i) exploitation of electricity-based RES (mainly wind and solar); ii) electrification of final uses; and iii) electricity exchange through efficient distribution and transmission networks [46]. The realization of the electricity triangle paradigm can guarantee multiple benefits in environmental, economic and social terms and can incentivize the deployment of RES in total final consumption [46].

The PhD dissertation will individually deepen the elements of the triangle, exploring two main topics: i) the electrification potential of the building sector; and ii) the deployment of centralized RES plants and planning of large-scale interconnections to transfer green electricity. The main introductory aspects and the challenges associated to these topics are reported in the following sections 1.3 and 1.4.

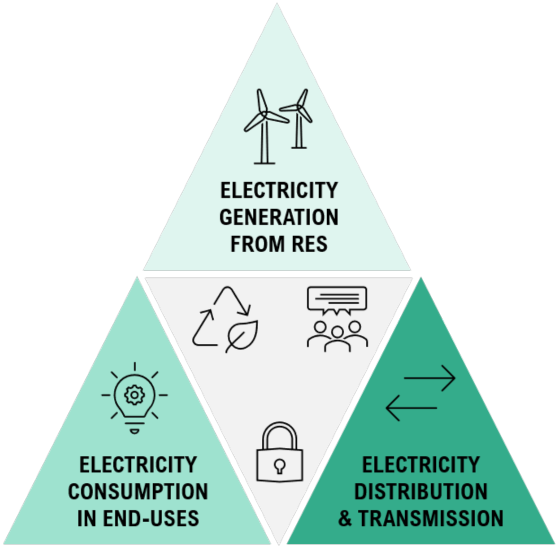


Figure 1.6: Electricity triangle: elaboration from Refs. [26, 41, 46].

1.3 Focus on building sector transition

Due to its significant energy and environmental impact, the building sector is acknowledged as a major player in the energy transition. At global level, buildings are responsible of almost 36% of total final energy consumption [47]. Direct CO_2 emissions represent approximately 10% of global emissions, and the value rises to around 30%, in case indirect CO_2 emissions from electricity and heat sectors are accounted [47]. According to the International Energy Agency (IEA) statistics, buildings consume approximately 55% of total electricity worldwide, and this value will further grow due to the expected increase of energy demand for space cooling [47]; indeed, electricity consumption will more that double by 2040, in case no measures for energy efficiency improvement are put in place [47]. The energy transition of the sector appears extremely challenging, but urgent, due to the existing pressure for improving the sector energy efficiency to sustainably meet an ever increasing demand [47].

According to the European Commission, most of the sector saving potential in EU is still untapped [48, 49], and, for this reason, the EU Roadmap to 2050 has pushed the sector to stronger efforts compared to other economic sectors, aiming to achieve a 90% reduction of emissions by 2050 compared to 1990 levels [50]. Over the years, and due to its potential for energy and economic savings, the building sector has been the main subject of diverse legislative directives and targets, at international and national level, among which it is worth mentioning the Energy Performance of Buildings Directive (EPBD), first published in 2002, recast in 2010 [51] and amended in 2018 [52]. The latter, in particular, is intended to push Member States (MSs) in setting strategic plans for the renovation of their building stocks, defined as "Long-Term Renovation Strategies" (LTRS) [52]. These plans aim to accelerate the cost-effective renovation of the existing EU building stock, increasing national renovation rates. Indeed, due to low new construction and demolition rates, it was estimated that around 70% of existing buildings will be still standing in 2050 [49], and approximately 75% of the current building stock is inefficient [53]. Despite the proven effectiveness of building renovation actions [53], only 1% of the national building stock is averagely renovated each year (with rates varying between 0.5% and 2.5% in the different MSs [48]), thus highlighting the efforts still required to the sector to meet the ambitious energy and climate mitigation goals. Effective renovation strategies for the next decades must be accompanied by science-based supporting tools for policy makers, in line with the afore-mentioned idea that scientific knowledge is fundamental to provide advice to policy makers. In particular, in order to monitor and set specific objectives, the LTRSs foresee the adoption of suitable Key Performance Indicators (KPIs), able to measure the progress of the monitored building stock in terms of decarbonization, reduction of energy consumptions and GHG emissions, and increase of non-energy-related benefits [48, 54]. Indeed, the renovation of the existing building stock will provide multiple benefits, among which improvements of buildings energy services, reduction of local air pollution with subsequent social benefits (i.e. reduction of health-related social costs [55]), reduction of energy poverty, creation of new jobs, and increment of financial savings [48, 54].

According to IEA, next generation buildings should be based on three fundamental pillars: sufficiency, efficiency and decarbonization [47]. The first term highlights the importance to avoid "unnecessary energy demand and technology investment", identifying proper renovation strategies that should not affect/reduce buildings energy services, while efficiency relates to the need of improving the energy performance of buildings, also thanks to the implementation of proper market and policy strategies able to push consumers towards the adoption of highly efficient and low-carbon technologies [47]; finally, decarbonization is used to indicate the need to shift from fossil to low-carbon solutions (mostly already present in the market), able to reduce the environmental impact of the sector, as well as to positively interact with energy and power systems, providing higher flexibility and reliability to energy networks [47].

From these considerations, it appears evident that the Heating, Ventilation and Air Conditioning (HVAC) sector will be in the crosshairs of building energy transition. However, if the spreading and diffusion of energy efficient and low-carbon solutions will be fundamental for the transition of the sector, the shift from conventional fossil fuels to low-carbon sources (among which electricity or biomass) will not be an easy task [47]. Thermal uses (both space heating and domestic hot water), which usually represent the highest share of buildings consumptions (especially in the residential sector) are identified as the services most difficult to decarbonize, due to several factors, among which economic (e.g. energy prices, split incentives associated with tenure status, etc.), technical (e.g. possible infrastructure interventions) or social barriers (e.g. consumers' preferences or lack of information or awareness on the benefits, either financial or not, guaranteed by the installation of alternative solutions) [47, 49, 56, 57, 58]. According to IEA, indeed, the progress of building heating technologies is still "off-track", since fossil-based technologies seem to be still preferable compared to more sustainable and efficient technologies, among which heat pumps or other renewable solutions (e.g. solar thermal collectors, etc.) [47]. For this reason, for the building transition to happen, policy intervention is essential. As reported in Ref. [48], building renovation decisions depend on several stakeholders and interested people (e.g. building owner, managers, developers, manufacturers, equipment installers, financial institutions, etc. [47, 48]), who can often have conflicting interests. Therefore, in order to effectively put in place suitable strategies and policy measures to unlock the savings potential of the sector, it is fundamental to understand which are the factors that most significantly influence decisions [48] and to boost and support a strong cooperation between the interested stakeholders [47]. Strong efforts at local, national and international scales are needed in order to effectively "push and pull policy measures to overcome known barriers and drive global market transformation towards energy efficiency in the coming years" [47]. In this sense, policy actions are fundamental in order to direct the transition of the sector in the medium- and long-term, and mainly to push the market to make low-carbon technologies, still not financially attractive for the consumers, more competitive. In order to help the transition of the sector in this direction, different tools can be used, varying from financial tools (i.e. incentive mechanisms) to economic ones (i.e. introduction of environmental taxes), or improving "policy regulations and market signals related to energy efficiency and CO_2 emissions in the buildings sector" [47].

The evolution of buildings energy demand has a significant impact on energy systems, and, thus, its assessment will be fundamental to evaluate the buildings interactions with other sectors, and particularly with the power sector. In this sense, electrification has been identified as crucial in the sector transition, and its role has been widely discussed in literature. According to IEA, indeed, "electricity is an important pillar of building sector decarbonization" [47], highlighting that electricity-fuelled technologies can be already competitive in the market, and thus could drive the transition of the sector, especially when coupled with a clean electricity generation mix. Heat pumps will be core protagonists in this transition, being characterized by high energy performance levels, allowing to deliver "a thermal output several times greater than the required electric input" [59]. If, on the one side, heat pumps can drive and push the decarbonization of the heating sector, on the other side, they can benefit from this decarbonization process [59]. Indeed, the electrification of the sector is more convenient when coupled with a renewable and clean power generation mix, which makes heat pumps (or generally speaking electricity-fuelled technologies) promising solutions to reduce the environmental impact of the heating sector and to increase the overall energy efficiency of the energy systems. In line with the recent Net Zero Emissions scenario by 2050, IEA forecasted that heat pumps will increase their share for meeting heating demands from 7% in 2020 to 55% in 2050 [60]. This trend is also in line with the expected increase of air conditioning demands, which will affect power systems capacity and infrastructure needs [47]. Furthermore, the electrification of the heating service through the exploitation of heat pumps can allow to absorb renewable power that could be potentially curtailed, thus efficiently using the capacity of intermittent RES to further increase electricity demand and to enable more flexibility [47].

However, the impact of an extensive electrification of end-uses on the power sector has been discussed by many authors, highlighting the risks that the process of heating electrification could bring [61, 62, 63]. Specifically, a large deployment of heat pumps in industry and building sectors might request reinforcements of the power system [61, 62]. Moreover, the increase of electricity peak demand, due to the increment of heat pumps, may cause congestion in the power networks. According to Gaur et al., "the widespread adoption of heat pumps faces several technical and socio-economic challenges", among which low public awareness and social acceptance, "lack of understanding of costs and environmental benefits arising from [heat pumps] HPs", absence of sufficiently trained professionals for the installation, or lack of an harmonized political framework supporting the spreading of such technologies at consumer level [61, 62]. Heat pumps in many market are still characterized by high investment costs, especially when compared to traditional fossil-based technologies; for this reason, appropriate "re-alignment of building codes, subsidies and taxes" can be beneficial for pushing these solutions in place of traditional ones [64]. However, heat pumps are considered a mature technology, and thanks to their high energy efficiency, they can guarantee significant energy consumption reductions, operational savings in the long-term [61], and reduction of local air pollution effects. For all these reasons, despite the barriers to be faced, Singh Gaur et al. concluded that heat pumps represent a promising solution to drive the energy transition of the building sector [61]. According to Thomaßen et al., the energy-related emissions generated by the building sector could be reduced by 10-15% using heat pumps, and this reduction can further increase in case heat pumps are associated to green electricity [59]. Moreover, in line with available research, electrification will assume a fundamental importance for the mitigation of the building sector impact, together with the deployment of "large-scale energy efficiency measures through improved technology and user behaviour" and the decarbonization of the supply side, also thanks to the "large-scale adoption of renewable energy" [65, 66].

In the PhD dissertation, the electrification potential of the building sector is studied by analysing its technological and political enablers, with a particular focus on heating and cooling sectors. The topic will be discussed in Chapter 2 and Chapter 3, analysing the building sector transition at two different scales: **micro scale**, related to the study of the potentialities and benefits of electric technologies and of their adoption at individual building level, and **meso scale**, analysing the diffusion of electric technologies in the entire national building stock, focusing on Italian residential buildings. At both micro and meso scales, through applicative studies, the research aims to analyse electricity-based technologies for buildings, comparing them with more traditional options, to value their performances and to highlight their benefits in terms of higher energy efficiency and reduced environmental impact.

1.4 Focus on large-scale paradigm of RES penetration and transmission expansion planning

As previously mentioned, the energy transition concept is usually linked to a wider deployment of renewables, which in turn demands and stimulates the process of electrification of final uses. Several authors have investigated the potential of renewable generation (mainly solar and wind power), from either a theoretical or a techno-economic perspective [26]. Among them, it is interesting to cite the work of Bompard et al. [26], in which authors estimated the theoretical potential of electricity generation from sun and compared it to the global electricity need. Specifically, comparing the 2014 total primary energy supply, authors stated that the "energy content of the solar flux reaching the Earth in two hours is able to cover the whole annual global energy needs" [26]. Moreover, translating this theoretical information in order to take into account the technical characteristics of existing PV technologies, according to authors' elaboration, it would be necessary to cover approximately 2.3% of world land with PV modules to meet global demand [26]. Also in line with the still untapped potential of wind and solar sources exploitation, these RES are experiencing a rapid technological development, confirmed by current data; indeed, according to IRENA statistics, wind and solar PV dominated overall renewable growth in 2018 [5], with estimated installations of 51 GW and 109 GW, respectively [67, 68].

A RES- and electricity-based transition will surely require a substantial transformation of the current power system. The increment of the share of variable and volatile RES (wind and solar) in the power mix asks higher flexibility to the power grid to deal with demand and supply fluctuations in real-time, thus increasing the needs and opportunities for cross-border (international and intercontinental) electricity exchange [69]. The expansion and reinforcement of the transmission grid will be fundamental to integrate more intermittent RES, as well as to limit the need for fossil-based back-up capacity [70] and to match the load in a reliable way [71, 72]. The possibility of implementing large-scale electricity interconnections among RES-rich areas and major loads has aroused significant interests, due to the possible benefits that those solutions could bring, among which improved security of supply, system efficiency, integration of RES, and higher system adequacy and reliability

[73, 74]. A detailed discussion on the possible benefits and risks associated to a global infrastructure was developed by Brinkerink et al., who also mentioned that one of the main reasons behind a global grid paradigm is the current disproportion between regions with abundant RES potential and those with high electricity demands [75]. An interconnected power system could potentially represent a cost-effective solution to exploit resources over large regions [76], to allow higher flexibility [77] and to reduce congestion in existing systems [78]. Large-scale interconnections can improve the connectivity between production and consumption centres, as well as reduce the impacts of local renewable energy fluctuations on the stability of local grids and promote the installation of generators in renewable-rich areas, even far from the main load centres [79]. Moreover, the development and use of widely scattered clean energy resources can assure a long-term and stable supply of energy, while reducing the costs of power supply [32]. Similar considerations are discussed by IEA, stating how cost-effective large-scale energy interconnections can bring the possibility to balance mismatches between supply and demand (taking advantage of time zones and regional diversities), thus helping to achieve higher flexibility and peak capacity savings [80]. Moreover, building large-scale interconnections can permit a higher integration of RES and to "access remote energy resources" (hydro, wind and solar sources are "location-specific") [80]. Undoubtedly, the realization of large-scale energy interconnections will involve significant investments on infrastructure, while promoting technological advancement and extensive applications of clean energy generation sources, Ultra-High Voltage (UHV) transmission lines, large-capacity energy storage, smart power distribution networks, and micro-grids [32]. A macro scale energy paradigm could have positive impacts also on society, promoting socio-economic development, creating new job positions in the RES industry, and reducing energy and environmental burdens [78, 32]. Moreover, power interconnections can help facing the future increment of population, economy, energy demand, and other elements that will have huge impacts on the future sustainable development [81].

However, it is fundamental to consider that, by definition, "interconnectors connect distinct jurisdictions" [80], thus potentially increasing the difficulties of large-scale projects realization, asking for cross-border collaboration [80]. Therefore, despite technological advancements needs, the future realization and growth of this power system paradigm will depend on considerations associated to market, regulation, and policy [80].

What has been said so far is in line with the ambitious Chinese vision of Global Energy Interconnection (GEI), designed by Z. Liu [32], which might represent a possible pathway for power systems towards decarbonization. GEI vision can be described as an extreme representation of the previously mentioned electricity triangle [26]. It is based on the promotion of a wider RES deployment, and mainly of solar and wind installations in Equatorial and Arctic regions, respectively, which can be efficiently utilized by converting them into electricity [32]. For the sake of exemplification, Liu forecasted that the total export capacities of wind power from the Arctic region would increase from 50 TWh to 3000 TWh from 2030 to 2050, while the export capacity of solar power from Equatorial region would increase from 870 TWh to 9000 TWh, from 2030 and 2050 [32]. To exploit the abundant RES potential at global level, transmission system improvement and development is fundamental. In particular, the main characteristic of the GEI vision is the High Voltage Direct Current (HVDC) backbone system, which allows to transfer power flows from remote RES-producing areas to the main demand centres (e.g. Europe, North America, and Asian countries) [32]. Supporting this vision, Bompard et al. compared HVDC and High Voltage Alternative Current (HVAC*) systems from a techno-economic standpoint, stating that, for long-distance interconnectors (higher than 2000-5000 km), the DC solution would be preferred [26].

Several authors have discussed and researched on GEI potentialities and limitations. According to Ref. [82], "GEI in nature is the combination of smart grids, ultra-high voltage transmission networks, and clean energy. Smart grids act as the foundation, bringing together advanced power transmission, smart control, new energy connectivity, new energy storage, and other modern smart technologies. It accommodates power from all types of clean energy sources in both centralized and distributed structures, accepts all types of smart appliances, and allows for interactive services. Thus, it coordinates between power sources, transmission networks, load, and storage, forms a structure featuring complementarity between different types of energy, and achieves highly efficient energy use" [82]. In line with this, despite the focus on a larger-scale paradigm, Liu's concept comprehends also the decentralization of energy systems as an important component of the next energy transition [32]. This topic is stressed also by Li et al., who discussed on the three GEI pillars ("high carbon to low carbon", "low efficiency to high efficiency" and "local balance to wider-scale distribution" [32]) and summarized GEI as the combination of renewable energy, UHV transmission networks and smart grids [83]. Indeed, as reported in Ref. [81], GEI could accommodate electricity generated through either central or distributed systems, allowing for high smart control, connectivity and flexibility.

Given the above, besides the technological aspects, the possible implementation of a GEI scenario will affect not only energy systems, but also economics, policy, and society, as discussed in Ref. [80]. A GEI paradigm, indeed, will involve a structural modification of energy systems, affecting the entire energy chain, and will have significant effects on the security of energy supply. The switch from fossil fuels to renewables could result in a reduction of the energy dependency on few countries, even if it could lead to new RES-based geopolitical implications. From a social standpoint, a large-scale paradigm based on efficient transmission grids and RES-based power can support the socio-economic growth of developing countries, increase their access to energy sources, and bring new opportunities for local capacity building and employment.

Among the possible interconnection-related benefits, the development of a global level analysis allows accounting for time differences between interconnected countries, as well as seasonal variations between hemispheres. Using an interconnected electricity system across the world, it may be possible to obtain relatively smooth load curves to realize the benefits of peak shaving and valley filling. The smoothing of electricity load curves is a major benefit of this new energy system paradigm, since the transfer of clean, renewable electricity can guarantee to use RES-electricity generation at its maximum, enabling its optimal allocation and consumption. This would, in turn, involve economic benefits, which can include, among others, shared reserves, higher reliability, enhanced competition, production and operational cost savings, capacity savings due to capacity requirements, recovery of (partly) stranded investments, and lower congestion costs.

However, despite the interests that this vision has aroused, the implementation of GEI faces several difficulties and barriers. Besides transmission technologies (UHV is achieving increasing technological maturity [80]) control techniques ("grid access to large-scale intermittent sources, voltage and frequency stability control, synthetic inertia generation and control, advanced protection, gas fault location and recovery, automatic recovery, etc." [26]) are fundamental in order to operate such systems. Moreover, as well described in Bompard et al., GEI encounters diverse fences in terms of policy and market aspects, among which, sovereignty, investment and cost allocation, benefit redistribution, and market schemes that need to be newly designed [26]. In particular, electricity trading and demand are expected to become critical factors in global energy markets, which should be completely re-designed in the view of a RES-based power system [26], asking for new market approaches, other than the traditional marginal pricing, in order to avoid zero prices for the long-term. Finally, interconnections will influence the geopolitical dimension. Infrastructure links and internet will become key aspects to control the main world powers [69]. Domination over neighbouring countries could be executed based on the ownership of electricity grids, making electricity cut-offs as strategic tools, similarly to what already happens for oil and gas sectors. However, differently from fossil fuels geopolitics, according to which only few states have control of fossil resources, countries with high energy dependence will have more alternatives, as importing electricity from close areas or producing electricity using local renewables. This means that there will be a complex network of electricity importers and exporters, but the asymmetry between them cannot be used as a geopolitical instrument [84]. For this system to be constructed and maintained, to overcome current obstacles, high levels of cooperation between the involved countries, governments and institutions need to be established [26], and the increments of cross-border electricity exchange will help in creating chances for further collaboration [69].

To conclude, in the view of more integrated and interconnected electricity systems, the expansion of the transmission network will be fundamental to accommodate higher RES-based electricity generation and to cope with the necessities and chances for cross-border electricity exchange [76]. In the PhD dissertation, attention is devoted to the extreme representation of this power sector transformation. Chapter 4 shifts the focus to the **macro scale**, analysing the impacts of a GEI-based global grid paradigm on mid- and long-term time horizons. The study aims to identify and quantify the potential challenges and/or benefits deriving from the realization of the GEI vision, providing explorative studies at global and European scales, also analysing the possibility to integrate non-technical factors into the modelling and planning of such infrastructure.

1.5 Research questions and scales of analysis

The research motivation starts with the realization that current energy systems are still mainly based on fossil fuels and that an energy transition has already started. As previously discussed, this changeover is often linked to a wider deployment of renewables, which in turn goes hand-in-hand with an expected higher electrification of final uses; their coupling can bring remarkable and multiple benefits and could be a key lever for decarbonization.

As a result of the former considerations, the research pathway is characterized by the overarching goal of assessing the role of electricity as a means for the energy transition, through different applicative studies with diverse focuses and levels of detail, by providing outcomes in the form of "usable knowledge", to support and guide the decision-making processes in different contexts of analysis. Specifically, the term "usable knowledge", coming from the political science field, can be defined as "accurate information that is of use to politicians and policy makers" [85], in line with the principle that better decisions come with better and more reliable information. Moreover, "[usable knowledge] must be seen as accurate, accessible, and contribute to the achievement of collective goals. It must represent consensus and be provided through a medium that is politically palatable" [85]. The term "usable knowledge" allows to pinpoint the connection between science and policy, highlighting how the role of science and scientists in supporting the energy decision-making process is crucial [86], for facilitating the creation of innovative policy alternatives or assisting and empowering effective policy interventions, providing more choice options to decision-makers [87].

Furthermore, as stated by Vijay et al., even though energy transition has global implications and dimensions, decisions are usually undertaken at local level by individuals and policy makers [3], thus highlighting the importance of assessing energy transition at different scales, analysing possible national- or local-based circumstances, which can influence the energy transition pathways. Moreover, a complete energy transformation process encompasses specific transitions of sectors (e.g. industry, transport, residential, etc.) and services (e.g. heating, lighting, cooling, etc.), each characterized by specific technological and policy pathways and in turn influencing (and influenced by) economic and socio-political aspects [1]. As reported by Bompard et al., each sector needs to transition towards low-carbon systems and services, "by enhancing the penetration of different technologies" [26], and this consideration highlights the importance of looking at the energy transition challenges also from an individual perspective.

In the light of the above, dealing with the complexity of energy transition processes and the involvement of multiple actors in their achievement, three overarching questions span the entire research pathway, integrating the analysis of the role of electricity in the energy transition with the challenges set to science, to provide science-based outcomes to support stakeholders in the decision-making process:

- how can electric technologies be valued and promoted to be among the protagonists of the energy transition?
- which instruments can be used to provide "usable knowledge" to inform and support the involved decision-makers?
- how can stakeholders' perspectives and interests be integrated and included in energy evaluations at different scales?

Encouraged by the external *stimuli* deriving from the international and national projects the candidate had the opportunity to work on, the PhD activities decline the research objectives and questions at different scales, focusing both on demand-side and supply-side transformations and targeting the main stakeholders potentially affected by them. Through diverse applications, moving the lens from a technological to a global perspective, the work focuses on three scales (micro, meso, macro), aiming to discuss some of the current challenges of the energy systems and the role of electricity in their transition. Specifically, the analyses are developed at different levels, from technological, to national, to European and global, focusing on two main topics, related to the increasing electrification of end-uses (giving attention to the building sector) and to the need for stronger policy support for a large-scale transmission expansion planning. In line with this, the three overarching research questions formerly cited are further deepened and tailored depending on the analysed context, as reported in Figure 1.7.

At **micro scale**, attention is devoted to study which technological solutions could drive the energy transition of the building sector, giving special attention to electricity-based ones (i.e. heat pumps, polyvalent heat pumps), and to define the appropriate methods and instruments to assess their operations and to value their technical, environmental and financial performances. On the one side, the analysis at micro scale is targeted to commercial stakeholders, mainly sellers and/or manufacturers, interested in valorizing efficient and sustainable technological solutions, able to respond to the new energy needs within the building sector (e.g. new occupants' habits, increasing temperatures due to climate change, etc.). A particular attention is devoted to the polyvalent heat pump, a still not widespread but promising solution, and to the assessment of its performances, also in comparison with those of more traditional all-electric HVAC configurations, aiming to surpass the existing modelling and regulatory gaps related to its enhancement and characterization. The developed analysis allows to deepen the following question: *which instruments can be used to properly assess and express the capability of polyvalent heat pumps to respond to new energy needs challenges?*

On the other side, the work intends to investigate the drivers and motivations of the main stakeholders involved in retrofit decision-making, focusing on the possible interests of consumers, generally driven by financial convenience, and of policy makers, mainly interested in pushing the market towards the adoption of low-carbon solutions to reduce the environmental impact of the sector. In particular, starting from the consideration that more environmental-friendly technologies can still be not financially attractive for the private consumers, the research wants to investigate how environmental-friendly technologies can be properly valued. The developed analysis allows to deepen the following questions: *how can environmental-friendly solutions be valued? Which instruments can help policy makers in preventing the diffusion of more environmental-risky solutions?*

Moving from single technology/building to the entire building stock, the **meso scale** application aims to simulate a scenario awarding the diffusion of more environmental-friendly solutions in the stock for satisfying the residential thermal uses. The meso scale study describes the development of medium- and long-term scenario analyses, run in order to forecast the diffusion of electricity-based technologies in the building sector at national scale, exploring an hypothetical condition in which the expected benefits of more environmental-friendly solutions could be used to drive consumers' choices towards their adoption, also thanks to the use of effective policy measures. Aiming to estimate the potential of electrification of the analysed building stock, the research investigates which tools in the hands of policy makers could help increasing the diffusion of electric solutions in the stock. In line with the previous analysis, the actors considered in this application include both private consumers and public entities. The developed analysis allows to deepen the following questions: *how can environmental benefits drive consumers' choices towards the adoption of more environmental-friendly technologies? Which instruments can help policy makers in increasing the penetration of environmental-friendly solutions?*

Finally, the applications at **macro scale** change the focus of the research, moving to supply-side transformations, focusing on large-scale transmission expansion issues in the view of a RES-based energy paradigm. In this case, the scale of interest is enlarged up to the global and European scales, analysing the current challenge of transmission expansion planning under the premises of the GEI vision. The applications aim to estimate the potentialities and implications that the realization of a global infrastructure of large-scale electricity interconnections could have. In this case, attention is mainly devoted to macro-players, among which regional, international or national policy makers, transmission system operators (TSOs), institutions and public authorities, being those having the power or interest to support or reject a development strategy [88]. Due to the intrinsic complexity and multi-dimensionality of the power and transmission expansion field, the research aims to investigate the possibility of integrating non-technical factors (e.g. social acceptance, political stability, etc.) into the modelling and planning processes. The developed analysis allows to deepen the following questions: *how can the potentialities of a global infrastructure of large-scale electricity interconnections be assessed? Which instruments can be used to include non-technical factors in the planning and modelling process?*

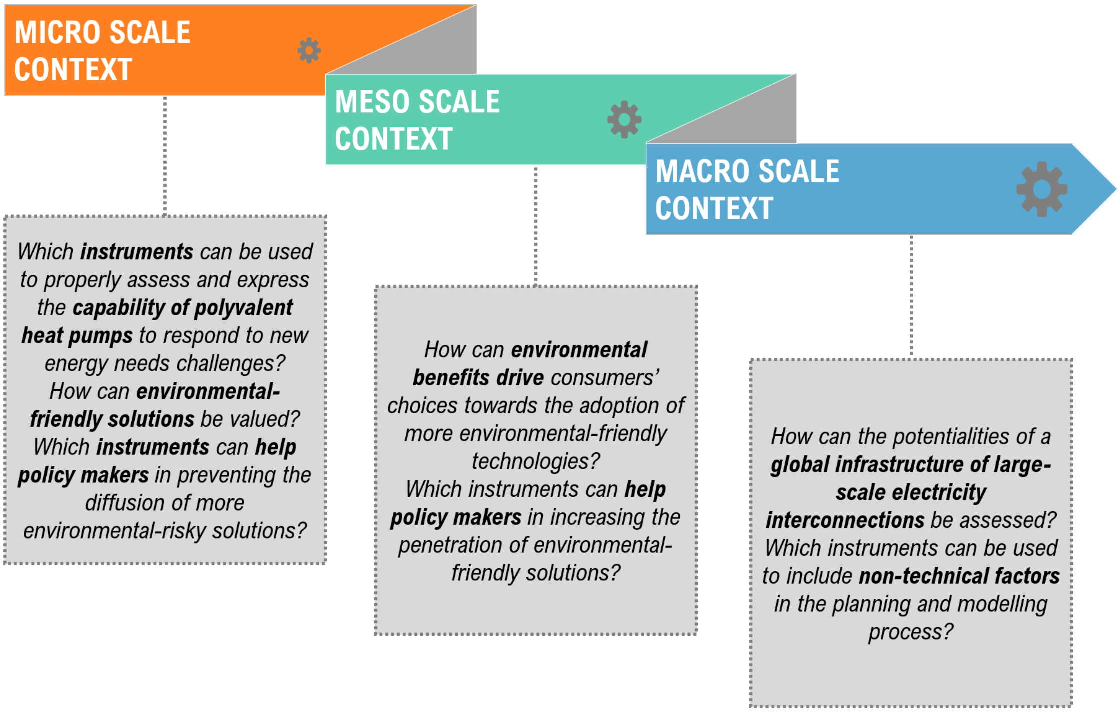


Figure 1.7: Key research questions at micro, meso and macro scales.

1.6 Towards a multi-layered methodological approach

The main topics addressed in the PhD dissertation cannot be studied from a purely energy perspective, but need to consider and integrate the possible interactions between the different dimensions embraced by their realization (e.g. social impacts, economic aspects, political challenges and opportunities, etc.). For this reason, these themes must be tackled with a multi-dimensional perspective, able to integrate elements belonging to different dimensions or layers of analysis (e.g. society, economics, policy, etc.) and to reflect the perspectives of the main stakeholders potentially involved or influenced by these challenges (e.g. policy makers, consumers, commercial entities, etc.).

TERMINOLOGY

The term "MULTI-DIMENSION" is used to indicate the multiple and interacting dimensions (i.e. energy, economic, political, social) that are touched by or can influence the energy transition phenomena. The expression "MULTI-LAYERED" is used with the same meaning, considering synonyms the terms "dimensions", "layers" or "domains".

The term "MULTI-SCALE" is used to indicate the multiple contexts of analysis, ranging from a micro scale (e.g. single technology, individual building), to a meso scale (e.g. national building stock), to a macro scale (e.g. region, group of regions, or the entire globe).

The term "MULTI-PERSPECTIVE" is used to indicate the multiple perspectives, motivations or decisions of the stakeholders involved in or influenced by the energy transition phenomena.

In this context, Key Performance Indicators (KPIs), multi-dimensional metrics and evaluation tools, energy modelling and long-term scenario analyses are identified as crucial instruments to inform and support decision-making processes. In particular, indicators are typically defined as a "strong tool in the hand of policy makers" to understand existing challenges [89] and to identify possible rooms for improvement. According to Alwaer et al., an indicator is a tool intended "to provide a measure of current performance, a clear statement of what might be achieved in terms of future performance targets and a yardstick for measurement of progress along the way" [90]. Indeed, KPIs allow to efficiently and clearly provide information on a phenomenon or a strategy [91], and to describe and synthesize complex problems [92], even at different scales and levels of knowledge [3]. Indicators selection or development should be tailored depending on data availability, resources and time, as well as on the interests and scopes of the stakeholders' groups involved in the planning processes [93]. According to Ref. [94], effective indicators must meet some fundamental criteria. Specifically, KPIs should be representative and able to inform in decision-making processes; simple and comprehensible also by non-expert audience; flexible, multi-purpose and sensitive to change; able to reflect conditions and perspectives impacting the current and future evolution of the described phenomenon; cost-effective and scientifically valid [94]. According to Kraan et al., indicators must be "sufficiently broad to characterize the system, relevant for policy and business decision-making and concise enough to facilitate smooth communication with and between (non-) experts" [95]. In other words, KPIs definition, which should always be done in line with the objectives, needs and interests of the involved stakeholders, allows to measure the current performances of energy systems, to set and monitor medium- and long-term objectives, but also to translate measured data into science-based usable knowledge, to be easily understandable by different users, also non-expert.

In line with this, indicators are commonly used in energy studies, with diverse aims, from measuring to monitoring, from supporting to informing, and are considered as essential elements for energy planning purposes [96]. Information on the possible low-carbon transition of energy systems is achieved thanks to the development and use of appropriate energy models [97]. According to Lund et al., energy modelling is exploited mainly to "assist in the design, planning and implementation of future energy systems" [98]. The development of an energy model is done by "identifying and highlighting certain parts of reality in order to focus on the most important aspects in relation to one's specific purpose" [98]. Indeed, energy models can differ in terms of scale, ranging from macro to micro, with diverse geographical and temporal granularity, focusing on specific sectors or technologies [98], depending on the analysts' objectives.

Energy models are essential to explore, assess and compare alternative energy scenarios [99], aiming to comprehend future and sustainable pathways for the energy systems under investigation [100]. Indeed, if energy modelling is fundamental for the design and implementation of future energy systems [98], the exploration of their possible directions is usually performed through long-term scenario analyses [101]. According to Kraan et al., scenarios can be defined as "quantified narratives of future pathways" [95], while de Geus identified them as "tools for foresight" [102], as they allow to understand and forecast future trends of energy consumption, generation or investments [103]. Their use allows policy makers and involved stakeholders to "debate policy options, monitor policy effectiveness and discuss trade-offs between various technology, system and value chains" [95]. Indeed, as reported in Becchio et al., scenario analysis allows to predict the effects that specific measures or policies can have on the analysed energy systems, assuming specific exogenous boundary conditions [103]. For this reason, scenarios are broadly used for energy planning purposes and for supporting and guiding the decision-making process [103, 104], allowing to study the evolution of the energy systems with different goals, time (short-, medium- or long-term scenarios) or spatial scales (from global to national to local) [105, 106].

In line with the previous discussion, energy systems and their advocated low-carbon transition are intrinsically made of social, political and economic elements [88]. For this reason, they cannot be described just in technical terms, but they need to be addressed in a holistic way, integrating all their possible domains and facets [88]. In other words, since the impacts and benefits of energy transition cross the boundaries of energy systems and affect environmental and socio-economic spheres, there is the need for multi-disciplinary methodological approaches, able to integrate the different dimensions of energy issues, as well as the diverse (and often contrasting) perspectives of the involved stakeholders into the modelling and forecasting of future energy systems. Indeed, the multi-dimensionality of the energy transition process has profoundly influenced energy modelling practices, asking to represent energy systems with a multi-layered approach, and considering the possible "interdependencies between policy making, energy infrastructure expansion, market behaviour, environmental impact and supply security" [107]. Therefore, in response to this, the elaboration of appropriate multi-dimensional methods for decision-making support in the energy (and power) sector is crucial [108], to tackle all its intrinsic complexity [15] and, hence, to involve and connect stakeholders with multiple perspectives, interests and objectives (mainly contrasting among them), as well as to integrate the various facets of energy issues [15, 88].

In this context, multi-dimensional or aggregate indicators are often used in order to assess the performance of an energy system by integrating/coupling diverse dimensions in a unique value; as reported by Mayer et al., the aggregation of more indicators into a single index allows to obtain "a simplified, coherent and multi-dimensional vision of a given system" [109]. In other words, the development of such aggregate metrics allows to study and assess energy systems with a multi-perspective approach and, thus, to identify the potential trade-offs between the different dimensions or perspectives. Moreover, diverse multi-dimensional evaluation tools have been introduced in support of energy modelling practices; indeed, being instruments capable to integrate different elements, belonging to diverse and often contrasting domains, these methods represent powerful solutions to guide energy policy makers to articulate plans representing the best compromises between multiple perspectives and objectives [15]. Among these methods, multi-criteria decision analysis (MCDA) tools are particularly useful for helping decision-makers in developing rationale and consistent preferences, needed to take confident decisions [110]. MCDA represents a suitable approach for policy decision-making, being able to integrate different criteria and to actively involve the main actors. For these reasons, multi-criteria techniques have been widely deployed in decisional processes regarding environmental issues [111], and are acknowledged as beneficial in providing to interested stakeholders an instrument to select the best strategical option or to rank the studied alternatives, in accordance with their needs and goals [112, 113].

All these considerations highlight the importance of dealing energy transition studies with a multi-disciplinary approach, able to combine insights from energy, economic, social and political dimensions. In the light of the above, the PhD research pathway attempts to respond to the current challenge set to science, which should effectively provide evidences in support of decision-makers. To accomplish this, a multi-layered methodological approach is defined, aiming to provide a scientific basis for supporting and guiding the decision-making process in different contexts. In detail, the developed methodological framework is organized around four main steps, as shown in Figure 1.8: *study*, *synthesize*, *simulate* and *support*.

The *study* step consists in the identification of the main influencing criteria and the definition of the key indicators that could describe and drive the phenomenon

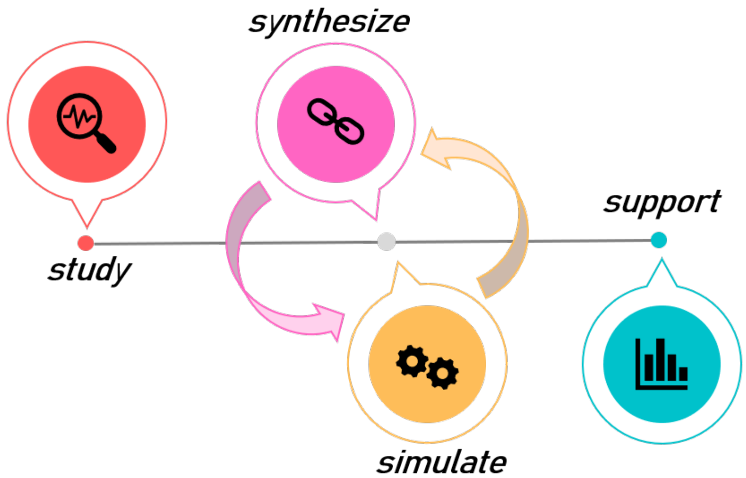


Figure 1.8: General steps of the defined multi-layered methodological approach.

under study; this step allows also to identify the main stakeholders involved in or influenced by the investigated energy transition phenomenon. Once defined and characterized the context, two combined steps are carried out. The *synthesize* step considers the need to integrate the different drivers through the definition of aggregate metrics or the use of appropriate evaluation methods (e.g. SWOT analysis, MCDA, etc.); both instruments allow to assess the performances of the energy systems under investigation with a multi-dimensional perspective, considering the potential conflicts among the assessed dimensions or stakeholders' perspectives. Starting from the development of appropriate energy modelling of the systems under consideration (e.g. a single technology, a building, a building stock, a power grid, etc.), the *simulate* step consists in the simulation of the operation of the analysed energy systems and/or in the development of appropriate exploratory scenario analyses, to evaluate the evolution of the energy systems in the medium- or long-term and to assess the effects of different policy strategies on their evolution. These steps are connected to each other, since depending on the situations and applications, the *simulate* step can be used as input to the *synthesize* one (allowing the calculation of aggregate metrics to evaluate the performance of the system under investigation), or vice versa, in case evaluation tools or synthesized metrics are used to drive the modelling or simulation phase. Finally, in the vein of science-based decision-making support, the *support* step consists in the development of proper graphical or analytical tools to be used for supporting the decision-making process and for providing outcomes in the form of "usable knowledge", easily comprehensible also by a non-expert audience.

The four steps of Figure 1.8 (*study*, *synthesize*, *simulate* and *support*) are applied at the micro, meso and macro scales formerly introduced, suitably tailoring the methodological framework in the different scales to respond to the specific research objectives and questions. A graphical synthesis of the main elements touched in the different applications is reported in Figure 1.9, summarizing the technologies and stakeholders considered in the different scales of analysis and highlighting the key instruments and methodological aspects supporting the achievement of the research objectives. All these elements will be further deepened in the following chapters of the dissertation.

To conclude, the scalability and multi-dimensionality of the presented methodological framework represents the main novel aspects of the research pathway. Moreover, as previously cited, attention is devoted to target the main stakeholders being influenced by or having the power to influence the transition processes, as well as to study the potential effects of appropriately defined policy strategies on stakeholders' decisions and expectations and on energy systems evolutions.

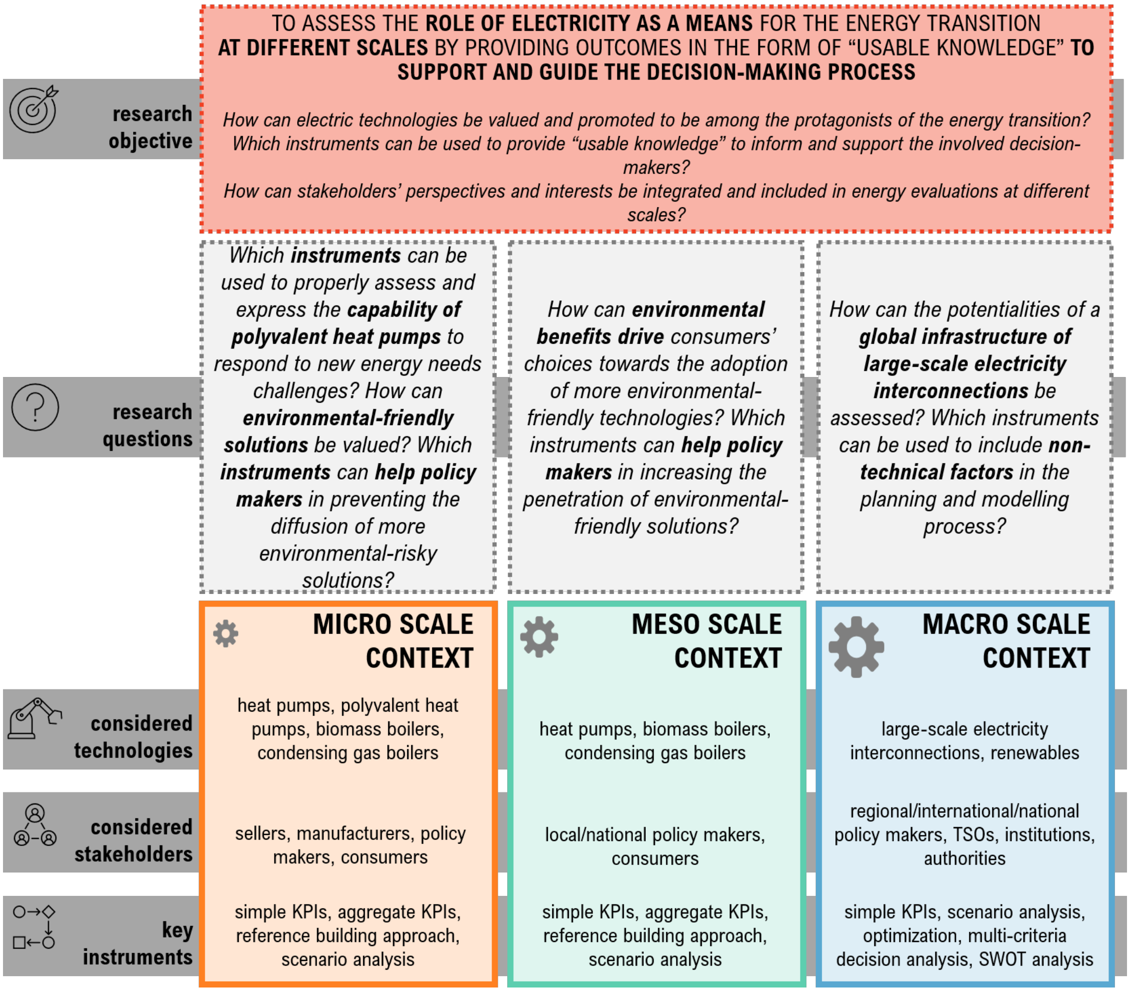


Figure 1.9: Graphical synthesis of the PhD roadmap: research questions and scales.

1.7 Roadmap and guidelines for the reader

This section aims to guide the readers within the dissertation, which, besides the hereby introductory section, is divided into three core chapters, each having the scope of addressing to some extent the challenges previously discussed. A graphical representation of the PhD thesis structure is summarized in Figure 1.10, to guide the readers within the dissertation.

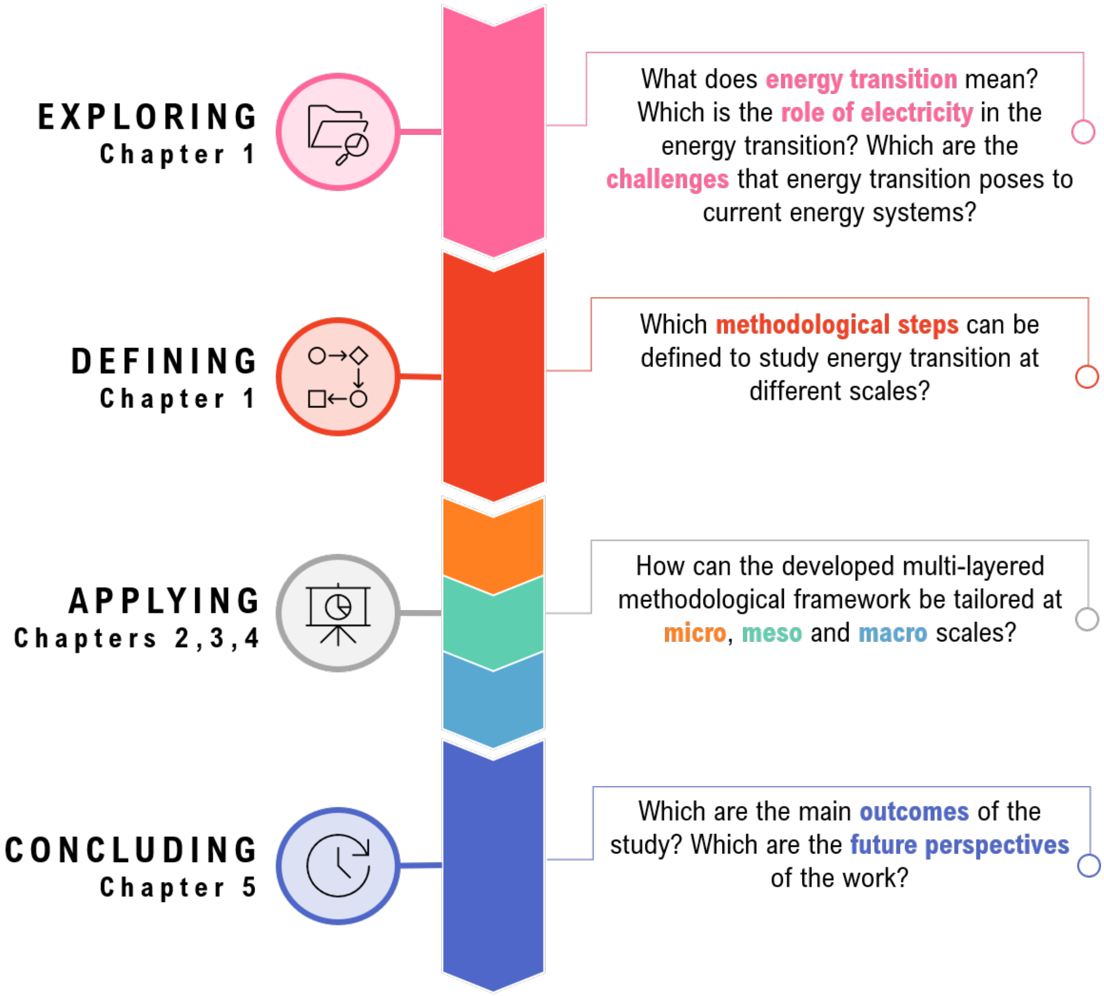


Figure 1.10: PhD thesis structure.

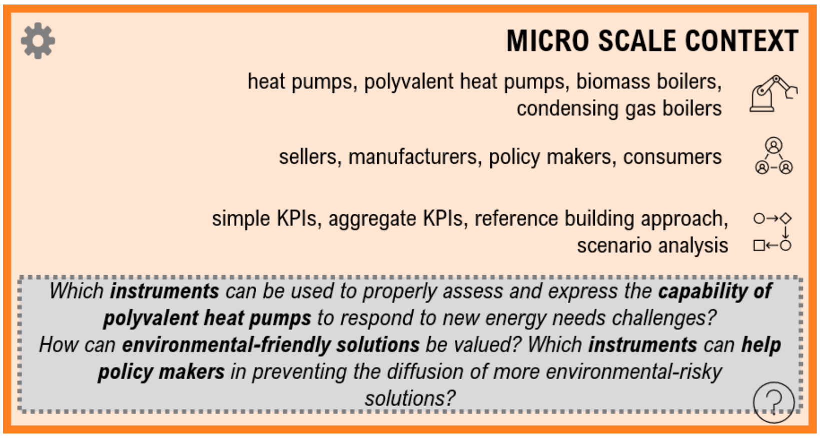
The PhD thesis intends to highlight the multiple facets of the current energy transition phenomena. To accomplish this, the methodological framework summarized of Figure 1.8 is applied and contextualized at different scales, each deepened in the diverse core chapters, also thank to the different international and national projects the PhD candidate had the opportunity to work on. Each core chapter provides an initial overview of the main context in which the research fits, a description of the main methodological steps of the analysis, showing how the general framework of Figure 1.8 is detailed and scaled depending on the context, and of the main motivations and assumptions for the case study; finally the key findings and conclusions are summarized, highlighting the main limitations of the applications and their possible future developments.

In detail, Chapter 2 focuses on the building sector transition and describes two applications at micro scale, both aiming to define appropriate indicators to value technologies, for either market-oriented or policy-oriented purposes. In Chapter 3, the analysis moves to the meso scale (national scale analysis), exploring how indicators for the valorization of environmental-friendly solutions for buildings can be used for forecast-oriented purposes. Finally, Chapter 4 shifts the focus to supply-side considerations and discusses applications at macro scale, related to energy scenario analysis and multi-dimensional energy planning of large-scale electricity interconnections at global and European scales, according to the Global Energy Interconnection vision.

To conclude, Chapter 5 draws the main conclusive remarks and the possible future perspectives the work opens the way to.

Chapter 2

Micro scale context



In line with the challenges imposed to the building sector, this chapter focuses on the technological scale, aiming to identify and develop proper numerical experimentations and graphical/analytical tools to valorize promising HVAC systems and technologies that could become main actors of the sector transition, giving greater attention to electric solutions. The chapter is focused on the development and use of simple and aggregate multi-dimensional KPIs as tools for evaluating effective commercial and policy strategies, highlighting how their definition must be strongly related to the objectives the analyst is willing to reach and control.

This chapter is divided in two parts, each describing a specific application at micro scale. The first part ("Indicators to value technologies for market-oriented purposes") is concentrated on the modelling of all-electric solutions, with a particular attention devoted to the polyvalent heat pump technology, a promising - but still not widespread - solution in the heat pump market. By the development and use of ad-hoc KPIs, the work aims to value the polyvalent heat pump in terms of technical performance. Moreover, proper multi-dimensional KPIs are used to compare the unit with other HVAC configurations, aiming to value its exploitation in terms of capability of service provision. In other words, the first objective can be intended as commercial- or industrial-based, aiming to value the polyvalent heat pump from a seller's or manufacturer's perspective; the second objective, instead, helps looking at the problem from the standpoint of an investor or costumer, who wants to "buy" a certain service, to be provided by the most cost-effective HVAC configuration. In this application, attention is mostly devoted to the characterization of the units operation dynamics; conversely, heating and cooling demand profiles are not linked to specific end-uses or building categories (e.g. residential, commercial, etc.), being solely characterized in terms of time (i.e. contemporaneity of heating and cooling requests) and load intensity.

The second part ("Indicators to value technologies for energy planning-oriented purposes"), instead, aims to shift the attention to a policy perspective, studying the variation of the competitiveness of market-diffused HVAC technologies (among which heat pumps), when the environmental benefits they guarantee are put on the table. The technological favorability for a private stakeholder (e.g. investor, occupant, owner, etc.) in terms of financial convenience is linked to the perspective of a policy maker, who wants to identify the risks associated to these financially-based decisions in the medium- and long-term, and thus aims to investigate the potential performances of less environmentally-risky technologies in case their environmental benefits are suitably valorized. In this application, a multi-domain aggregate KPI is developed, aiming to couple the contrasting private and public perspectives into a single metric, in order to value the benefits that more environmental-friendly solutions can guarantee. Differently from the previous study, the technological solutions are not fully characterized in terms of operation dynamics, while attention is devoted to the characterization of the heating demand to be satisfied, in turn linked to specific building typologies, locations, and thermo-physical properties, taking advantage of the reference building approach. Due to more comprehensive data on residential buildings, the technological competitiveness is investigated in order to respond to the space heating demand of typical buildings representative of the Italian residential stock.

2.1 Indicators to value technologies for market-oriented purposes

2.1.1 Overview

It is well known that the building sector is among the most environmentally impacting economies at global level, and, clearly, HVAC systems play a fundamental role in the attempt of reducing its consumptions and emissions. To achieve the ambitious targets set by the European Union in terms of higher energy efficiency and lower environmental impact for the building sector, more efficient and sustainable technologies should be used to provide air conditioning services. In this context, the polyvalent heat pump can be considered a promising solution. What distinguishes this technology from the traditional reversible heat pump is its capability to provide space heating and cooling simultaneously and independently. Therefore, its adoption could help achieving a stronger reduction of fuel consumptions and GHG emissions, with respect to other alternative technologies. Since these efficient solutions are still little exploited, few efforts have been dedicated to them in literature, both in their modelling and in the definition of appropriate KPIs to better characterize them and exploit their potential benefits. The work discussed in this section allows to fill this gap, aiming to highlight the peculiarity and potentialities of these technologies, emphasizing the need for performance metrics and KPIs appropriately defined for their enhancement. The analysis allows to develop a simplified computational flow to model the operation of these complex units. Moreover, attention is devoted to the development of new component-level KPIs for estimating the technical performances of the polyvalent heat pump according to diverse boundary conditions (i.e. contemporaneity, climate, load intensity) and to the identification of a set of multi-dimensional KPIs (i.e. belonging to technical, financial and environmental spheres) for comparing polyvalent units with more traditional electricity-fuelled HVAC configurations.

Keywords Advanced HVAC systems, electric technologies, polyvalent heat pump, hourly modelling approach, Key Performance Indicators, simultaneous heating and cooling loads.

Declaration The topics described in this chapter were previously published in the following publications:

- M. Vio, C. Becchio, S.P. Corgnati, **G. Crespi**, M. Babuin, S. Morassutti, *The Polyvalent heat pumps technology in retrofit of existing HVAC systems*, Energy Procedia 133, pp. 158-170, 2017 [114].

- I. Abbà, **G. Crespi**, S.P. Corgnati, S. Morassutti, L. Prendin, *Sperimentazione numerica delle dinamiche di funzionamento di sistemi polivalenti*, Proceedings of

AICARR Conference 2020: 37° Convegno Nazionale AiCARR - Obiettivo 2030: Scenari, tecnologie e strategie per la sostenibilità energetica nella climatizzazione, 9-10 July 2020 [115].

- **G. Crespi**, I. Abbà, S.P. Corgnati, S. Morassutti, L. Prendin, *HVAC polyvalent technologies to balance contemporary loads in buildings*, to be published in the proceedings of SDEWES conference, October 2021, *accepted as archival paper after peer-review process* [116].

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2.1.2 Background

The definition, development and use of appropriate Key Performance Indicators for quantifying buildings energy performance is essential for driving the transition of the building sector [117]. Specifically, the knowledge of the actual performances of a building or an energy system allows to make reasonable retrofit choices, as well as to perform "fault detection and diagnostics, retro-commissioning and measurement and verification" [117], mainly in existing buildings.

According to Li et al., building services are characterized by a hierarchical structure, which is reflected in the different levels of KPIs potentially usable for their assessment: i) "whole-building-level"; ii) "system- or service-level"; and iii) "component- or equipment-level" [117]. Specifically, in their work, authors refer to component as an individual equipment or appliance within a building (e.g. lighting system, boiler, chiller, etc.), while a system is intended as the "aggregation of individual equipment and components that delivers a particular building service" [117]. Furthermore, when aiming to evaluate the performance of a building or system comparing it with codes, standards or existing benchmarks, the assessments can be classified according to two main approaches: i) "feature-specific" methods, which aim to check the presence of a particular technology or service in a building; and ii) "performance-based" methods, which provide quantitative information on the performance (not only energy) of the use of the analysed systems [117].

Whole-building-level KPIs are typically used in order to give a snapshot of a building performance, and can be either quantitative or expressed in rating scores (e.g. Smart Readiness Indicator, Whole Building Performance Indicator, etc.) [117]. During the PhD path, diverse applications dealt with the assessment of buildings performances in these terms. For the sake of exemplification, in Ref. [118], a reference hotel building and diverse retrofit scenarios were assessed (for the climates of Milan and Bari) and compared using specific whole-building KPIs, tailored for the hotel category. The models were simulated through EnergyPlus software and the computed KPIs[1] were compared with literature-based benchmarks, in order to provide a comparative analysis of the hotel energy behaviour with respect to the average performances of hotel buildings for the same location and with similar characteristics [118]. Furthermore, recent work focused on feature-specific approaches. Specifically, the Smart Readiness Indicator (SRI), introduced by the EPBD recast of 2018 to push the smart building revolution [52], can be brought in this category of methods. The SRI is intended to score a building readiness to smartness (with a percentage score from 0% to 100%), by identifying the smart-ready services present within the building (e.g. automatic control of heating systems, automatic control of shading systems, etc.) [52]. The indicator, which is calculated based on a multi-criteria assessment, represents an example of whole-building-level KPI. The SRI assessment was investigated by the PhD candidate, with a particular interest in understanding its capability of providing information also in energy efficiency terms. In particular, in Ref. [119], authors applied the SRI assessment methodology to an office building (i.e. the Energy Center at the Politecnico di Torino), aiming to explore the sensibility of the indicator to possible energy efficiency improvements of the building. To do this, energy dynamic simulations of new smart-ready services to be implemented in the case study were parallelly conducted together with the re-assessments of the SRI, in order to verify if reductions of energy needs (assessed through energy simulations) were reflected also in improvements of the overall SRI score for the Energy Center [119]. Finally, a review described in Ref. [120] focused on the use of certification schemes and rating scores for assessing a building performance. The review aimed to compare different energy labels for hotel buildings, in order to evaluate which schemes were actually able to express the energy performance of the buildings under investigation (rather than pushing the diffusion of the "green washing" phenomenon) [120].

Despite the widespread use of whole-building-level indicators, as stated by Li et al., such KPIs are not able to fully evaluate the performance of the energy systems in a more detailed way and, thus, "to assess and diagnose the building performance with a higher resolution, system-level and component-level evaluations are necessary" [117]. If component-scale KPIs are more diffused and mature, since they are mainly used in assessing the performance of an equipment in line with building labels or codes (e.g. COP or EER of a heat pump/chiller, etc.), system-level KPIs are less covered [117]. However, these indicators are becoming increasingly more interesting, since they allow to evaluate the total performance of a multi-component system, rather than the efficiency of a single component [117]. Moreover, the spreading of digitalization and building management and control

[1] Annual energy consumption in $kWh/m^2/y$, annual energy consumption per room in $MWh/room/y$, GHG emissions per room in $tCO_{2eq}/room/y$ or per floor area in $kgCO_{2eq}/m^2/y$, as well as GHG emissions per room per night in $kgCO_{2eq}/room/night$ [118].

systems allows to deepen the real performance of building systems, thus offering new perspectives and instruments for defining detailed and informative KPIs [117].

This consideration is particularly valid for the HVAC sector, which represents one of the most consuming voices among the building consumptions [121]. Indeed, due to the significant impact that HVAC systems have on the overall consumption of a building [117, 122], there is the necessity to boost the adoption of increasingly more efficient and sustainable technologies, always without compromising indoor air quality and occupants' thermal comfort and well-being. The transition of the HVAC sector needs to face the changes in energy demand due to occupants' habits and behaviours (i.e. the diffusion of smart working activities as a consequence of the COVID-19 pandemic), as well as to climate change effects. Indeed, as reported in Byrne et al., the combination of thermal envelope improvements, the increase of electricity consumption for electrical equipment and of domestic hot water (DHW) demands (especially in residential buildings) is leading to new energy needs, as the simultaneous (or "slightly delayed") heating and cooling requests [123]. Moreover, the improvement of buildings energy efficiency in the building sector is fundamental to face the increasing demand for air conditioning, mainly due to the increase of external temperatures due to climate change effects [46, 124]. If, on the one hand, energy efficient technologies and solutions already exist in the market to favour buildings transition, on the other hand, the reduction of their energy consumptions is hampered by the increase of cooling needs of both residential and commercial buildings, due to the recent increment of temperatures. Indeed, it is undoubted that climate change and global warming is affecting the way buildings operate, changing typical heating and cooling profiles, and thus is having (and will strongly have) relevant impacts on air conditioning consumptions.

The change of energy demand profiles opens the way to energy systems considerations. Indeed, these new challenges and necessities for the sector are shifting attention towards more efficient and sustainable generation technologies, which will be asked to promptly respond to these needs to easily satisfy in a cost-effective way even simultaneous space heating and cooling demands [115, 116]. Traditional HVAC systems are mainly composed of separate and independent units to serve space heating and space cooling. Generally, space cooling is provided through the use of chillers, which remove heat from the ambient to be cooled and reject it to the atmosphere, and are driven by electricity (through compressors); space heating, instead, is generally provided by fossil fuels generators, which produce hot water [121]. However, in recent years, the European air conditioning market is pushing towards the exploitation of electric solutions also for heating purposes, achieving energy efficiency improvements, reduced environmental impact and significant energy consumption reductions [61].

In this framework, the polyvalent heat pump (PHP) technology is recognized as a promising solution [121]. The novelty of this technology, if compared with the traditional reversible heat pump (HP), is the capability to provide space heating and space cooling simultaneously and independently, and not only seasonally (as traditional HPs). A literature review on multi-function heat pumps is provided in Ref. [123], in which authors summarize some examples of possible building categories or situations which could request contemporary (and opposite) heating and cooling needs; specifically, residences, hotels or glass-fronted offices represent clear examples of building categories which can experience significant requests for simultaneous needs, especially during mid-seasons, or for north- and south-oriented zones. The PHPs use is particularly interesting in modern buildings (mainly non residential), where it is possible to experience the need for both space cooling and heating at the same time, or in a limited timespan, and cooling and heating loads are usually comparable [121]. In these situations, indeed, the heat removed from the ambient to be cooled could be used to satisfy heating loads in other building zones or for DHW purposes, instead of being rejected. If this cannot be guaranteed when having two independent systems for cooling and heating purposes, which are not able to interact between them, polyvalent heat pumps allow this "saving" operation. As reported in Ref. [114], the use of a polyvalent heat pump allows to halve the energy consumptions compared to traditional technologies. In particular, among the main benefits this solution could guarantee, it is possible to cite the reduction of life-cycle and running costs (both energy and O&M), the reduction of primary energy use and the decrease of overall GHG and air pollutant emissions [121], with associated reduction of health-related social costs [55].

Even though the potential of the PHP technology is recognized, mainly at commercial level, few literature exists on its modelling and valorization. Indeed, most of the existing studies mainly refer to specific case study applications, aiming to estimate the energy savings deriving from the adoption of the polyvalent technology, especially in commercial buildings [114, 116, 125, 126]. Moreover, as stated in Ref. [116], there is a gap in literature on the possible metrics or KPIs to be used in order to value PHPs operations and benefits, also when compared with other widespread systems. In relation to this, it is worth mentioning that, regarding the HVAC sector, and specifically the heat pump market, which is of interest for this study, most of the KPIs traditionally used for its assessment are component-based. This is the case of the annual performance metrics COP (Coefficient of Performance) or EER (Energy Efficiency Ratio), which are typically used to assess the heating and cooling performances of heat pumps and chillers, as well the seasonal SCOP (Seasonal Coefficient of Performance) and SEER (Seasonal Energy Efficiency Ration) indices. However, if these approaches and metrics are suitable for HPs, and are diffused both at commercial and private (investor/consumer) scales, a similar approach for PHP is still missing. Indeed, to the best of the candidate's knowledge, to date, there is no shared methodological approach able to model the polyvalent heat pump behaviour and to estimate its benefits through the use of appropriate KPIs, easily understandable especially by industries and professionals. For the sake of exemplification, the mentioned SEER and SCOP metrics, introduced by EN 14825 standard and commercially used to indicate the performances of heat pumps, are not suitable enough for the PHPs performance assessment, as will be discussed later.

Therefore, the technological improvement in the air conditioning sector asks for new component- and system-level indicators, able to respond to these new challenges. Specifically, at component-level, new KPIs are needed in order to include the assessment of the hours of contemporary heating and cooling demands. Moreover, when comparing the performance of a PHP with respect to traditional HVAC systems, there is the need to scale up the attention from the single component to the entire multi-units system able to match the requested demands. Indeed, when considering the need for simultaneous heating and cooling demands, if the PHP can intrinsically meet the contemporary services with a single unit, other traditional HVAC systems, instead, require the combination of more units operating in parallel to provide the same services, requesting a shift from the single component (i.e. a single mono-function unit) to the entire system (i.e. combination of one or more units).

This topic is particularly relevant in current research and commercial environment, even though in literature attention is mainly devoted to component- and system-level KPIs expressing the performance of HVAC systems from a purely technical or energy standpoint [117]. However, to express the benefits that PHPs can guarantee, it is fundamental to look at the problem from a multi-dimensional perspective, identifying also proper KPIs touching the economic and environmental domains. In line with the above, the micro (or technological) scale application here provided aims to:

- define a common and homogeneous numerical modelling approach to simulate the behaviour of PHPs and other selected HVAC systems and to match demand and supply through specific algorithms;
- develop and use proper KPIs to evaluate the effective performances of the PHPs, to be coupled with traditional market-diffused metrics;
- define a set of multi-dimensional KPIs to valorize the benefits arising from the installation of PHPs in place of more traditional technologies, comparing different all-electric HVAC configurations.

The developed methodological approach is tested for a set of HVAC configurations, including PHPs, using real data of commercial units from Rhoss S.p.A technical documentation.

The polyvalent heat pump technology

The polyvalent heat pump (or hybrid heat pump) represents a "smart" and innovative solution, in all cases of contemporary requests of heating and cooling services in some hours of the year. The unit is compatible with different configurations of air conditioning systems and could be applied in either 2- or 4-pipes systems, guaranteeing high flexibility and efficiency. Specifically, 2-pipes systems are characterized by the presence of a single water circuit used for both space heating and cooling. Therefore, in these systems, the hydraulic circuit is fed by chilled or hot water, depending on the season, and a summer/winter switch is present, to permit the seasonal changeover; in this configuration, all terminals work in the same way, providing either space cooling or heating (not simultaneously). Conversely, 4-pipes systems present two independent circuits, one fed with chilled water for space cooling and one with hot water for space heating [121]; in this case, terminals present two independent coils, which can cool or heat, depending on the ambient load. This configuration allows to make all zones independent, without requiring any seasonal changeover, since both services can be provided in any time.

Focusing on the operation mode, the PHP can be identified as an heat pump equipped with an heat recovery system, which permits the unit to operate in three different modes (heating, cooling or combined modes). Each polyvalent unit is equipped with three heat exchangers [121]: i) the main heat exchanger, used to produce either hot or chilled water; ii) the secondary heat exchanger (or heat recovery system), used to produce only hot water; and iii) the evaporator/condenser, used for heat absorption or rejection, depending on the operation mode. This latter component can be a finned coil for air-cooled systems or a refrigerant-to-water heat exchanger for water-cooled systems [121]. Per each operation mode, only two heat exchangers are active. Differently from traditional reversible HPs, which shift between cooling and heating mode with a seasonal changeover, PHPs can shift their operation mode in every moment, depending on the requirements [121].

In this work, attention is restricted to air-to-water PHPs and to 4-pipes systems, in which chilled water is produced at the main heat exchanger, while hot water is provided by the secondary one. To demonstrate the benefits associated to an automatic management of the water supply system, three automatic modes are considered, namely *Heating Only* (A3), *Cooling Only* (A1), and *Contemporary Heating & Cooling* (A2) modes. The PHP working principle is shown in Figure 2.1. Specifically, when the A3 mode is active, the machine works as a traditional non-reversible heat pump, providing hot water to the secondary heat exchanger; when the A1 mode is operating, instead, the unit works as a chiller, producing cold water at the main heat exchanger; finally, in the A2 mode (active only in case both heating and cooling services are simultaneously requested by the user), chilled and hot water are produced at the main and secondary heat exchangers, respectively.

Focusing on the A2 combined operation mode, the unit is able to recover the heat removed from the evaporation (cooling mode), which otherwise would be wasted. This is an advantage not solely in energy terms (allowing to provide an heating service simultaneously with cold water production), but also in economic terms, since it allows using a "free" heat quota, without fuel expenditure for its

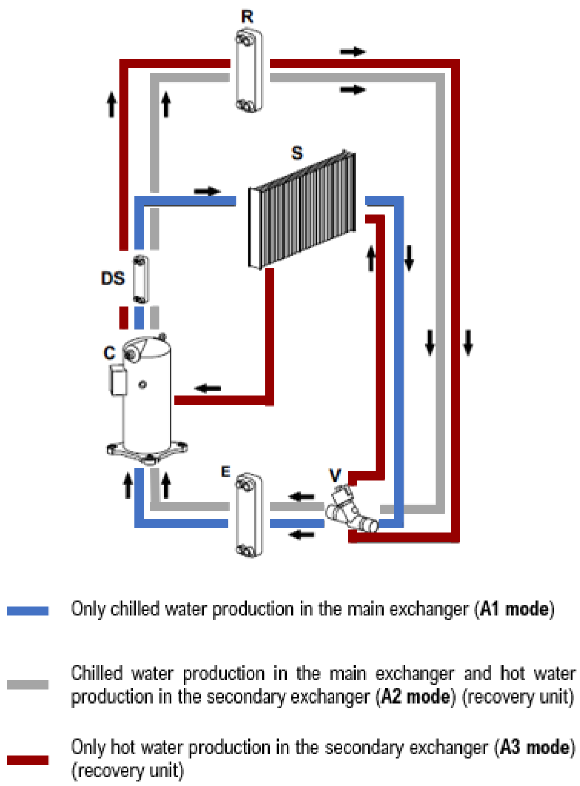


Figure 2.1: PHP working principle. S = evaporator/condenser; C = compressor; E = main heat exchanger; R = secondary heat exchanger (recovery unit); V = lamination valve; DS = desuperheater (auxiliary).

production. Therefore, it follows that the polyvalent unit has two main advantages; firstly, the possibility to provide heating and cooling services simultaneously, easily responding to occupants' needs; then, the heat recovery is completely "free" and, thus, it guarantees energy consumptions, costs and emissions reductions. PHPs can be exploited in diverse sectors, from residential buildings, to hospitals, from offices, to hotels, to commercial buildings. Indeed, both residential and non residential buildings could experience the simultaneous need of heating and cooling in some periods of the year. This could be due, for instance, to the presence of high glazed surfaces in some building zones, as well as to the different solar exposition of the envelope components, or to the diversities in terms of occupants' preferences and needs. In all these cases, the more the loads are requested in contemporaneity, the higher the potentiality of the PHP is and this issue will be further discussed in the following sections through the modelling exercise.

2.1.3 Methodology

Aiming to fill the existing literature gap in terms of PHP valorization, the analysis couples a new modelling approach with the development of suitable KPIs for PHPs enhancement. The methodology consists of two phases, as graphically summarized in Figure 2.2:

- **study and simulate: numerical experimentation**. The most significant variables influencing the units operation are identified and a numerical model is developed to simulate their working dynamics.
- **synthesize and support: definition and computation of relevant KPIs**. Appropriate simple KPIs, able to properly value PHP performances and to compare them with other HVAC configurations, are developed and computed.

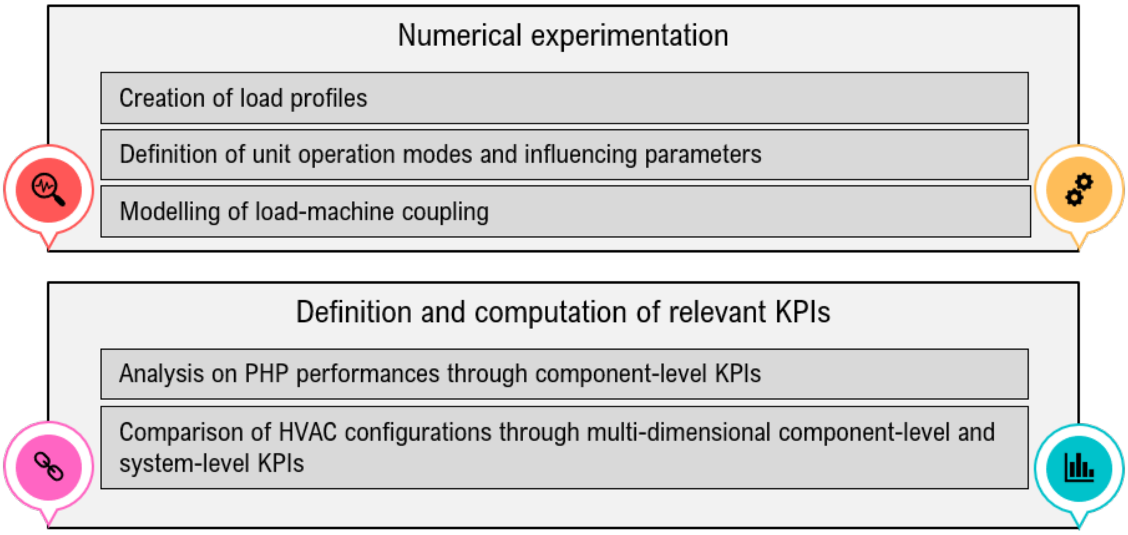


Figure 2.2: Main methodological steps.

Specifically, the developed numerical experimentation aims to model the coupling of buildings heating and cooling thermal loads with specific operation curves characteristics of the investigated machines. Moreover, based on the modelling approach, energy metrics in term of cooling and heating capacities and absorbed electrical energy consumptions (for each operation mode) are estimated, permitting the definition of specific indicators. The numerical calculation is divided into three main steps: i) creation of load profiles; ii) definition of unit operation modes and influencing parameters; and iii) modelling of load-machine coupling. The first step of profiles creation was performed in *MATLAB*®, while all the following calculations of load-machine coupling were developed in specific Excel spreadsheets [115, 116, 127]. Then, the methodology consists in the definition and computation of appropriate KPIs, both simple and aggregate, to investigate the units performances, and in the identification of energy, environmental and financial metrics to compare the units with other HVAC configurations. Indeed, this phase is developed around two main objectives: i) analysis of PHP performances through component-level KPIs; and ii) comparison of HVAC configurations through multi-dimensional component- and system-level KPIs.

Study and simulate: numerical experimentation

Creation of load profiles In order to generalize the methodology and to render it applicable for diverse end uses, a new theoretical model was proposed, not dependent neither on real load profiles, nor on energy dynamic simulations. The approach involved the use of theoretical Gaussian curves, chosen due to the similarity of their shapes with real load curves. In particular, the Gaussian-shaped load curves were created to express the influence of the time variable on the PHPs performances. Specifically, based on the coupling of heating and cooling load curves, it was possible to calculate the percentage of contemporaneity, where contemporaneity is intended as the simultaneous request of both heating and cooling in the i_{th} hour of the year. This quantity is calculated as in Eq. 2.1:

$$\%_{cont} = \frac{H_{cont}}{H_{year}} \tag{2.1}$$

where H_{cont} represents the sum of the hours of contemporary heating and cooling requests during a year, while H_{year} indicates the 8760 hours of the year. In order to avoid a 100% contemporaneity, a curtailment of values smaller than 10% of maximum values was imposed [115, 116, 127].

Based on the Gaussian load profiles, it was possible to distribute the loads between the operation modes. It is important to specify that the developed model allows only two operation modes to be active each hour, depending on the load conditions. Therefore, five possible operation modes are granted: 1) only A1 ($A1_{ncont}$); 2) only A3 ($A3_{ncont}$); 3) only A2; 4) A2 + A1 (indicating A1 as $A1_{cont}$); and 5) A2 + A3 (indicating A3 as $A3_{cont}$).

Per each hour, heating $P_H(i)$ and cooling $P_C(i)$ loads were associated to one of the five operation modes. During the non-contemporaneity hours, for $A1_{ncont}$ and $A3_{ncont}$ modes, the quota $P_{C,A1,ncont}(i)$ and $P_{H,A3,ncont}(i)$ were calculated, by associating to each non contemporaneity hour the cooling and heating loads of the Gaussian profiles. During contemporaneity hours (H_{cont}), instead, the main condenser is by-passed and substituted with the heat recovery, which allows to recover a certain portion of heat, which was assumed equal to 30% more than the delivered cooling power. In this case, the heating ($P_{H,A2}$) and cooling ($P_{C,A2}$) thermal loads associated to A2 mode were defined per each hour, in order to avoid excess of heating energy. In some hours, it is possible that A2 mode is not sufficient to cover all the contemporary loads, requesting the integration with A1 ($P_{C,A1,cont}$) in case cooling load is greater than heating load, or with A3 ($P_{H,A3,cont}$) vice versa.

Definition of unit operation modes and influencing parameters Technical documentation from Rhoss S.p.A company was used in order to build the operation curves of the polyvalent heat pumps under investigation. Specifically, declared capacities and coefficients of performance for different temperature and partial load conditions were gathered, based on which absorbed electricity consumptions were calculated.

The performances of air-cooled systems are strongly dependent on two factors: external air temperature and partial load operations. The first dependency is particularly relevant, since air is the external source of the unit for both heating and cooling. A linear relation between capacities and external air temperatures was considered by extrapolating the data provided by constructors (at -7, 2, 7, 12°C for heating and 20, 25, 30, 35°C for cooling, in line with Ref. [128]), and by using linear interpolation for the other temperature values. As for the dependency on partial loads, capacities and coefficients were extracted from technical documents, obtaining 10 steps, from 10% to 100% of the nominal power.

This methodology is valid for A1 and A3, while A2 operation mode requires an additional consideration. During H_{cont}, the main condenser is by-passed and substituted with the heat recovery. For this reason, in A2 mode, there is no contact with the external air source (the unit behaves as a water-to-water heat pump) and, therefore, the performances are no longer dependent on external air, thus varying solely according to partial load conditions.

Modelling of load-machine coupling Once defined the hourly load profiles and the polyvalent heat pump operation mode characteristics, a model of load-machine coupling was developed, able to combine the effects of temperature and partial loads conditions on the unit performances, as well as to couple demand and production with an hourly time-step [115, 116, 127]. The numerical model, per each hour of the year, associates the appropriate machine operation mode to the requested load, taking care of the external air temperature. However, the effects of both influencing parameters are not independent, and thus it was necessary to combine them. To do so, firstly, the capacity at partial load was calculated using Eq. 2.2:

$$C(PL)(i) = L(i) \cdot \frac{DC_{nom}}{DC(T_{ext})(i)} \tag{2.2}$$

where:

- i is the i_{th} hour of the year;

- T_{ext} is the hourly external temperature in $°C$;
- PL is the partial load percentage;
- $C(PL)(i)$ is the capacity at the partial load percentage $PL(i)$ in kW;
- $L(i)$ is the requested load at the i_{th} hour of the year in kW;
- DC_{nom} is the full load capacity at nominal conditions in kW;
- $DC(T_{ext})(i)$ is the capacity as a function of the sole air temperature T_{ext} at the i_{th} hour of the year.

At this point, the partial load capacity $C(PL)(i)$ needs to be associated to the real machine operations at partial load $DC_{PL}(i)$, in line with the following conditions:

- if the load is higher than the i_{th} capacity, the polyvalent heat pump works with the i_{th+1} capacity;
- if the load is higher than the maximum limit (100%), the polyvalent heat pump works at full load and a back-up system is activated in order to match the remaining demand;
- if the load is lower than the minimum limit (10%), the polyvalent heat pump works at the lowest partial load condition.

Finally, to combine both effects (i.e. external temperature and PL conditions), the final capacity and absorbed electric power were calculated as in Eq. 2.3 and 2.4:

$$DC(T_{ext}, PL)(i) = DC_{FL}(T_{ext}) \cdot \frac{DC_{PL}(i)}{DC_{nom}} \tag{2.3}$$

$$P_{el,abs}(T_{ext}, PL)(i) = P_{el,abs,FL}(T_{ext}) \cdot \frac{P_{el,abs,PL}(i)}{P_{el,abs,nom}} \tag{2.4}$$

where:

- DC_{nom} is the full load capacity at nominal conditions in kW;
- $DC_{FL}(T_{ext})$ is the full load capacity as a function of the sole external temperature in kW;
- $DC_{PL}(i)$ is the partial load capacity at the partial load percentage $PL(i)$ in kW;
- $P_{el,abs,nom}$ is the full load absorbed power in nominal conditions in kW;

- $P_{el,abs,FL}(T_{ext})$ is the full load absorbed power as a function of the sole external temperature in kW;
- $P_{el,abs,PL}(i)$ is the partial load absorbed power at the partial load percentage $PL(i)$ in kW.

Eq. 2.3 and 2.4 are valid for A1 and A3 operation modes, which are dependent on both external air temperature and partial load conditions. For A2 mode, instead, equations were simplified as in Eq. 2.5 and 2.6, since this operation mode does not foresee a direct contact with the external source:

$$DC_{A2}(PL)(i) = DC_{PL,A2}(i) \tag{2.5}$$

$$P_{el,abs,A2}(PL)(i) = P_{el,abs,PL,A2}(i) \tag{2.6}$$

where:

- $DC_{PL,A2}(i)$ is the partial load capacity at the partial load percentage $PL(i)$ in the A2 mode in kW;
- $P_{el,abs,PL,A2}(i)$ is the partial load absorbed power at the partial load percentage $PL(i)$ in the A2 mode in kW.

Based on Eq. 2.3, 2.4 and 2.5 and 2.6, it was possible to associate each capacity with the relative coefficient of performance, depending on the operation mode.

Moreover, in case the PHP is not able to cover all the requested loads, an integration through an electric back-up system with unitary efficiency was assumed to provide the remaining thermal power, as in Eq. 2.7:

$$\begin{aligned} P_{BU,A1,cont}(i) &= P_{C,A1,cont}(i) - DC_{A1,cont}(T_{ext}, PL)(i) \\ P_{BU,A3,cont}(i) &= P_{H,A3,cont}(i) - DC_{A3,cont}(T_{ext}, PL)(i) \\ P_{BU,A1,ncont}(i) &= P_{C,A1,ncont}(i) - DC_{A1,ncont}(T_{ext}, PL)(i) \\ P_{BU,A3,ncont}(i) &= P_{H,A3,ncont}(i) - DC_{A3,ncont}(T_{ext}, PL)(i) \end{aligned} \tag{2.7}$$

Once all the powers involved in the process were defined, the total thermal energy for space heating and cooling and the relative electric absorbed energy can be calculated per each operating mode (Eq. 2.8 and 2.9). The total electric energy computations include also the needed back-up contributions (if any).

$$\begin{aligned}
E_{A1,ncont} &= \sum_{i=1}^{8760} P_{C,A1,ncont}(i) \cdot h(i) \\
E_{A3,ncont} &= \sum_{i=1}^{8760} P_{H,A3,ncont}(i) \cdot h(i) \\
E_{A2} &= \sum_{i=1}^{8760} P_{C,A2}(i) \cdot h(i) + P_{H,A2}(i) \cdot h(i) \\
E_{A1,cont} &= \sum_{i=1}^{8760} P_{C,A1,cont}(i) \cdot h(i) \\
E_{A3,cont} &= \sum_{i=1}^{8760} P_{H,A3,cont}(i) \cdot h(i)
\end{aligned} \tag{2.8}$$

$$\begin{aligned}
E_{el,A1,ncont} &= \sum_{i=1}^{8760} (P_{el,A1,ncont}(i) \cdot h(i) + P_{BU,A1,ncont}(i) \cdot h(i)) \\
E_{el,A3,ncont} &= \sum_{i=1}^{8760} (P_{el,A3,ncont}(i) \cdot h(i) + P_{BU,A3,ncont}(i) \cdot h(i)) \\
E_{el,A2} &= \sum_{i=1}^{8760} P_{el,A2,cont}(i) \cdot h(i) \\
E_{el,A1,cont} &= \sum_{i=1}^{8760} (P_{el,A1,cont}(i) \cdot h(i) + P_{BU,A1,cont}(i) \cdot h(i)) \\
E_{el,A3,cont} &= \sum_{i=1}^{8760} (P_{el,A3,cont}(i) \cdot h(i) + P_{BU,A3,cont}(i) \cdot h(i))
\end{aligned} \tag{2.9}$$

Synthesize and support: definition and computation of relevant KPIs

Analysis of PHP performances through component-level KPIs The first objective of this phase consists in the definition of new ad-hoc KPIs at component-level, to value the technical performances of the PHPs and to account for their ability of providing contemporary loads. In line with this, the following component-level KPIs were identified, all expressing the performance of the PHP units for the different analysed operation modes: non contemporary cooling ($A1_{ncont}$), non-contemporary heating ($A3_{ncont}$), contemporary cooling ($A1_{cont}$), contemporary heating ($A3_{cont}$) and contemporary heating and cooling ($A2$). Specifically, five indices were defined to evaluate the different operation modes during the contemporaneity and non contemporaneity hours, as reported in Table 2.1, and shown in Eq. 2.10, 2.11, 2.12, 2.13 and 2.14. It is worth mentioning that the eventual integration through a back-up system was considered in the calculation of the five component-level KPIs.

Table 2.1: New component-level KPIs for PHPs.

$CPnC$	Cooling only Performance in non Contemporaneity hours	Eq. 2.10
$HPnC$	Heating only Performance in non Contemporaneity hours	Eq. 2.11
CPC	Cooling only Performance in Contemporaneity hours	Eq. 2.12
HPC	Heating only Performance in Contemporaneity hours	Eq. 2.13
$SHCPC$	Simultaneous Heating and Cooling Performance in Contemporaneity hours	Eq. 2.14

$CPnC$ and $HPnC$ indicators were calculated considering the operation in cooling only ($A1_{ncont}$) and heating only ($A3_{ncont}$) non contemporaneity hours, respectively.

$$CPnC = \frac{E_{A1,ncont}}{E_{el,A1,ncont}} \tag{2.10}$$

$$HPnC = \frac{E_{A3,ncont}}{E_{el,A3,ncont}} \tag{2.11}$$

Even though these indexes can recall the standard-based [128] and commercially used $SEER$ and $SCOP$, there are some relevant differences in their computation and definition. Indeed, the proposed methodology differs from the standard one both in terms of load curves construction and energy needs temporal allocation. As reported in Ref. [116], standard EN 14825 proposes linear-shaped curves, directly dependent on outdoor air temperature [128]. Moreover, the frequency of temperatures occurring (and in turn the frequency and intensity of heating and cooling requests) is assessed associating a number of hours to each bin of temperature, according to three categories of climates: colder (Helsinki), average (Strasbourg) and warmer (Athens). Conversely, the hereby proposed numerical model does not directly correlate loads with external temperatures, since load profiles are based on theoretical Gaussian curves, distributed through the year; moreover, the model does not consider any temperature constraints for heating or cooling requests. These assumptions were done in order to overcome the main limitation of the EN 14825 standard, which does not permit any contemporaneity of requests, as well as to differentiate the performance of the PHP over its whole set of operation modes, giving greater attention to the contemporaneity performance.

For contemporaneity hours, three indicators were defined. Similarly to $CPnC$ and $HPnC$, CPC and HPC were developed in order to consider the operation of the unit in $A1_{cont}$ and $A3_{cont}$ (when the A2 mode alone is not enough to match the requested load). Finally, $SHCPC$ indicator aimed to isolate the PHP performance in the A2 operation mode, and thus to calculate the ratio between the total thermal energy requested (simultaneous heating and cooling) and the corresponding absorbed electricity (Eq. 2.14).

$$CPC = \frac{E_{A1,cont}}{E_{el,A1,cont}} \tag{2.12}$$

$$HPC = \frac{E_{A3,cont}}{E_{el,A3,cont}} \tag{2.13}$$

$$SHCPC = \frac{E_{A2}}{E_{el,A2}} \tag{2.14}$$

Starting from the above, a new aggregate KPI was proposed, capable of including all the units performances during contemporaneity and non-contemporaneity hours into a single metric, named Annual Weighted Index (AWI_{PHP}). In detail, this annual metric was obtained weighting the five component-level KPIs reported in Table 2.1 on the relative operation hours. More precisely, according to the load profiles (theoretical Gaussian curves), it was possible to isolate three major operation hours, identified as $H_{ncont,A1}$, $H_{ncont,A3}$ and H_{cont}. Based on these values, three coefficients were calculated, as reported in Eq. 2.15, 2.16 and 2.17.

$$\alpha = \frac{H_{ncont,A3}}{H_{year}} \tag{2.15}$$

$$\beta = \frac{H_{ncont,A1}}{H_{year}} \tag{2.16}$$

$$\gamma = \frac{H_{cont}}{H_{year}} \tag{2.17}$$

Moreover, in order to differentiate and isolate the hours to be associated to the diverse operation modes occurring during H_{cont} ($A1_{cont}$, $A3_{cont}$ and $A2$), γ was further disaggregated in γ_1, γ_2 and γ_3. Specifically, each contemporaneity hour was fractionated proportionally to the loads distribution between A2 and $A1_{cont}/A3_{cont}$ in that specific hour, when $A1_{cont}$ or $A3_{cont}$ is needed to integrate A2 working mode. According to this assumption, γ_1 is used to indicate the fraction of contemporaneity hours of $A3_{cont}$ mode, γ_2 the fraction of contemporaneity hours of $A1_{cont}$ mode and γ_3 the fraction of contemporaneity hours of $A2$ mode. This simplification was performed in order to guarantee that the total number of operation hours for the PHP would not exceed the 8760 hours of the year. These ad-hoc weighting factors were used in order to weight the correspondent metrics, as reported in Eq. 2.18.

$$AWI_{PHP} = \alpha \cdot HPnC + \beta \cdot CPnC + \gamma_1 \cdot HPC + \gamma_2 \cdot CPC + \gamma_3 \cdot SHCPC \tag{2.18}$$

Comparison of HVAC configurations through multi-dimensional component- and system-level KPIs The second objective of this phase consists in the identification of a set of multi-dimensional metrics at either component- or system-level, to compare PHPs performances with other all-electric HVAC configurations, being the loads equal, to value PHPs benefits in terms of capability of service provision. The considered configurations are identified as multi-units, since they require more units parallelly operating to provide the same services as the PHP. In this application, multi-units systems were always composed by a reversible heat pump that was differently coupled with other HVAC components (e.g. electric boiler, chiller, reversible heat pump, etc.), which are requested to work only during H_{cont} (during the non-contemporaneity hours, indeed, the reversible heat pump is able to provide cooling only and heating only, depending on the request). The multi-dimensional KPIs considered in the analysis are reported in Table 2.2, referring to three main dimensions: energy/technical, environmental and financial [116].

Table 2.2: New multi-dimensional KPIs for the comparison between PHPs and other multi-units HVAC configurations. C = component; S = system.

Domain	**Name**	**Extended name**	**Unit**	**C/S**	**Source**
Energy - Technical	$CPnC$	Cooling only Performance in non Contemporaneity hours	-	C	Eq. 2.10
	$HPnC$	Heating only Performance in non Contemporaneity hours	-	C	Eq. 2.11
	ACI	Aggregate Contemporaneity Index	-	C/S	Eq. 2.19
	$NSLP$	Non-Satisfiable Load Percentage	%	C	Eq. 2.20
	TPC	Total Performance Coefficient	-	C/S	Eq. 2.21
	AWI	Annual Weighted Index	-	C/S	Eq. 2.22
Environmental	CO_2	Annual CO_2 emissions	t_{CO_2}/y	C/S	-
Financial	$\Delta C_I\%$	Δ Investment Cost w.r.t PHP	%	S	Eq. 2.23
	$\Delta C_e\%$	Δ Energy Cost w.r.t PHP	%	S	Eq. 2.24

From the energy or technical standpoint, the systems were compared in terms of $CPnC$ and $HPnC$ metrics, which can be computed for all the analysed systems, focusing on the different performances of the units (i.e. PHP, primary reversible HP) during the non-contemporaneity hours. These indicators can be categorized as component-level KPIs, since they assess the heating or cooling performances of the PHP or the primary reversible heat pump during non-contemporaneity hours.

To analyse the behaviour of the HVAC configurations during the sole contemporaneity hours, an aggregate metric, called Aggregate Contemporaneity Index (ACI) was developed, able to represent the overall performance of both PHPs and other configurations during H_{cont}. As reported in Eq. 2.19, the metric was calculated for all configurations as the ratio between the heating and cooling contemporary requests and the associated electricity consumptions of the units.

$$ACI = \frac{E_{A2} + E_{A1,cont} + E_{A3,cont}}{E_{el,A2} + E_{el,A1,cont} + E_{el,A3,cont}} \tag{2.19}$$

This indicator can be considered either a component-level or a system-level KPI, depending on the HVAC configuration under investigation. More precisely, if, for PHPs, ACI is a component-level KPI, since cooling and heating needs are met using a single equipment, for multi-unit HVAC systems, more units are parallelly and independently run to satisfy heating and cooling loads; for these systems, therefore, ACI can be considered as a system-level KPI, since it evaluates a combination of more individual components for its computation [116].

To assess the performance of the single units composing the multi-units systems and, especially, to isolate the loads that the primary reversible heat pump would be able to satisfy alone, the Non-Satisfiable Load Percentage ($NSLP$) indicator was developed [115, 116]. It was calculated for the sole reversible heat pump of each j_{th} multi-unit configuration, estimating the quota of contemporary load non satisfiable by the primary reversible heat pump, in case it operates alone, without any integration unit. The indicator was calculated according to Eq. 2.20:

$$NSLP(j) = \frac{Q_{non-sat}(j)}{Q_{need}} \tag{2.20}$$

where $Q_{non-sat}(j)$ represents the load non satisfiable by the primary heat pump of the j_{th} configuration due to contemporaneity and Q_{need} is the total requested contemporary load.

Shifting to an annual performance assessment, two indicators were defined. TPC indicator, firstly introduced in Ref. [127], was calculated as the ratio between the total energy requested and the total electrical energy consumed, as in Eq. 2.21;

$$TPC = \frac{E_{A1,ncont} + E_{A3,ncont} + E_{A1,cont} + E_{A3,cont} + E_{A2}}{E_{el,A1,ncont} + E_{el,A3,ncont} + E_{el,A1,cont} + E_{el,A3,cont} + E_{el,A2}} \tag{2.21}$$

Moreover, similarly to the previous computation of the AWI_{PHP}, AWI was proposed (Eq. 2.22), obtained weighting ACI, $CPnC$ and $HPnC$ on their effective operation hours (using the weighting coefficients previously defined in Eq. 2.15, 2.16 and 2.17), to make all the configurations comparable. Indeed, the selection of the weighted metrics allows to calculate it either for PHPs or for the other multi-units systems. As already mentioned for the ACI, also TPC and AWI can be defined as component-level metrics for PHPs and system-level metrics for all other HVAC configurations.

$$AWI = \alpha \cdot HPnC + \beta \cdot CPnC + \gamma \cdot ACI \tag{2.22}$$

Moving from the purely technical sphere to other relevant dimensions, attention was devoted to environmental and financial indicators. Indeed, if the KPIs so far analysed can be classified as commercial or technical metrics, mainly reserved to value PHPs in the commercial/industrial field, the environmental and financial aspects are of interest also for private (investors/consumers) stakeholders. Going into detail, still focusing on a yearly evaluation, annual CO_2 emissions were computed for all HVAC configurations, using appropriate electricity emission factors. Furthermore, focusing on the financial sphere, two KPIs were selected in order to represent the convenience of the use of the PHP with respect to the other systems in differential terms (computed with respect to the PHP). More precisely, in order to better inform on the economic benefits of the PHPs with respect to other systems, $\Delta CI\%$ and $\Delta Ce\%$ were calculated as the percentage variations of investment and annual energy costs that would result in case PHPs are used in place of the other configurations (2.23 and 2.24) [116].

$$\Delta C_I\%(j) = \frac{C_{I,PHP} - C_{I,j}}{C_{I,j}} \tag{2.23}$$

$$\Delta C_e\%(j) = \frac{C_{e,PHP} - C_{e,j}}{C_{e,j}} \tag{2.24}$$

2.1.4 Case study

The described methodology was tested for the climate of Strasbourg, which represents the “average” reference climate according to EN 14825 standard [128]. Hourly external temperatures were gathered from the Photovoltaic Geographical Information System (PVGIS) tool [129]. An average percentage of contemporaneity of 52% was used as reference for the analysis; the normalized theoretical load profiles associated to this percentage of contemporaneity are reported in Figure 2.3. Maximum heating and cooling loads were set equal to 640 kW and 630 kW.

Four HVAC configurations were selected [116]:

- configuration 1 (C1): a reversible heat pump (6 scroll compressors, 660 kW) with cooling priority during H_{cont}, coupled with an electric boiler (500 kW) for heating integration;
- configuration 2 (C2): a reversible heat pump (6 scroll compressors, 660 kW) with heating priority during H_{cont}, coupled with a chiller (6 scroll compressors, 520 kW) for cooling integration;
- configuration 3 (C3): a reversible heat pump (6 scroll compressors, 660 kW) with no priority during H_{cont}, coupled with a small sized reversible heat pump (6 scroll compressors, 370 kW) for heating/cooling integration;

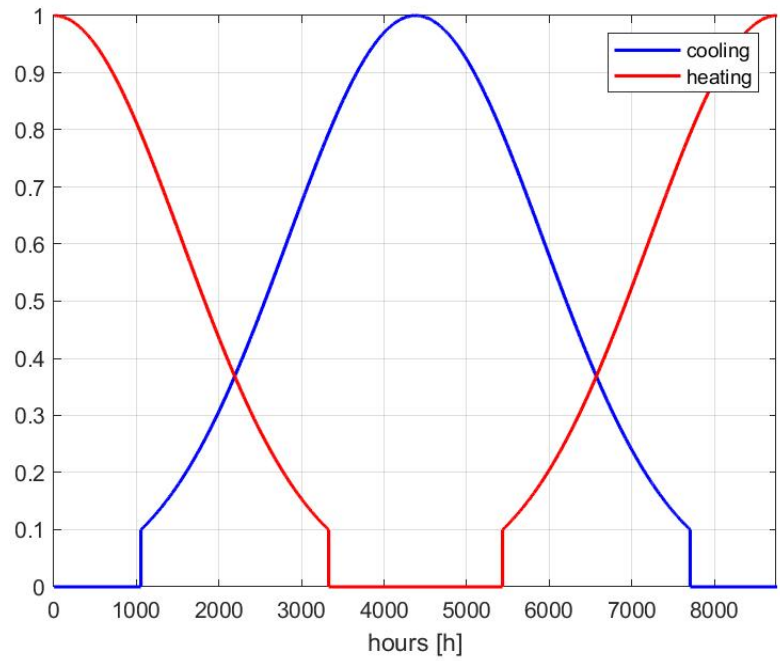


Figure 2.3: Gaussian load profiles for a 52% percentage of contemporaneity (curtailment imposed below 0.1).

- configuration 4 (C4): a polyvalent heat pump (6 scroll compressors, 660 kW).

For the financial KPIs, investment costs were assumed from market prices of Rhoss S.p.A units for PHPs, heat pumps and chillers, while Ref. [124] was used for the price of the electric boiler. A 0.42 kg_{CO_2}/kWh emission factor for electricity was considered [130].

2.1.5 Key findings and discussion

This section summarizes the key outcomes coming from the application. The first part is devoted to the sole PHP technology, in order to investigate its performances, as well as its dependence on the fixed boundary conditions, through proper sensitivity analyses. The second part, instead, is dedicated to the comparison of the PHP with the other selected HVAC configurations, through the entire set of defined multi-dimensional KPIs. Thanks to the general methodological approach, the same numerical experimentation was used for all the HVAC configurations.

The first methodological step allowed to create Gaussian-shaped heating and cooling profiles and to associate them to the real operation modes of the PHP unit. From the numerical model, energy demands for the Strasbourg climate and a 52% contemporaneity were extrapolated (as shown in Table 2.3). These values are not dependent on the HVAC configurations, which in turn affect the distribution of the operation modes between the units during contemporaneity hours.

Table 2.3: Annual energy demands (expressed in kWh/y).

Non contemporary cooling	**Non contemporary heating**	**Contemporary cooling**	**Contemporary heating**
1'231'417	1'251'604	1'138'314	1'156'383

Analysis of PHP performances through component-level KPIs

Focusing on the PHP technology, Figure 2.4 shows the load distribution into contemporaneity and non contemporaneity heating and cooling, for the defined boundary conditions in terms of climate and contemporaneity, while Figure 2.5 summarizes the percentage distribution of the operation modes for the PHP for the same boundary conditions. In particular, from Figure 2.5, it is possible to notice that the integrative electric back-up system is requested only in the peak hours during the heating season, while there is no need of integration during the cooling season.

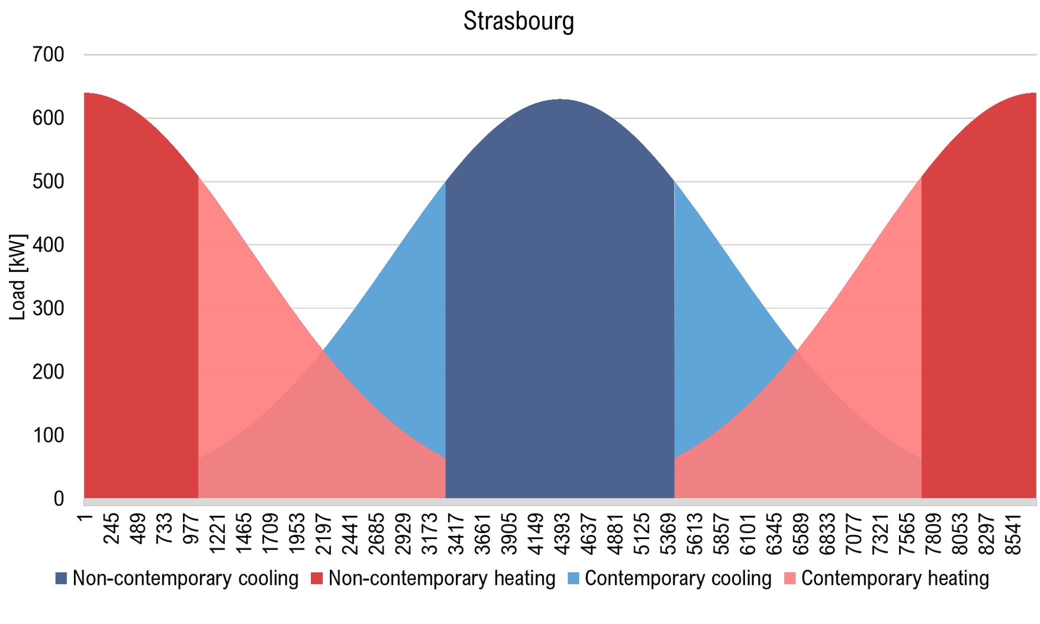


Figure 2.4: Load profiles for a 52% percentage of contemporaneity in absolute terms: Strasbourg climate.

Once fixed these boundary conditions, the component-level KPIs summarized in Table 2.4 were calculated.

As visible from Table 2.4, the PHP is characterized by a high efficiency for A2; indeed, thanks to the heat recovery in this operation mode, the heating capacity

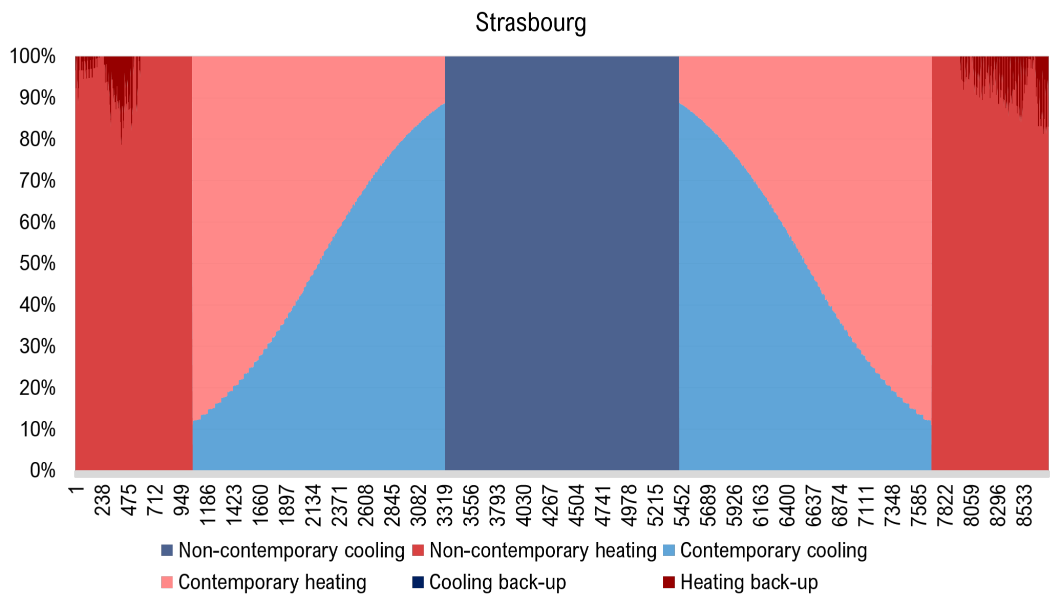


Figure 2.5: Distribution of PHP operation modes for a 52% percentage of contemporaneity in percentage terms: Strasbourg climate.

Table 2.4: Component-level KPIs for PHP: Strasbourg climates and 52% contemporaneity.

$CPnC$	$HPnC$	CPC	HPC	$SHCPC$
4.700	2.838	4.698	3.083	8.236

is a free quota, served without consuming any electrical power. When aggregating the performance coefficients into a single aggregate metric, an AWI_{PHP} of 5.12 is obtained. In its computation, the use of the weighting coefficients lowers the effect of the $SHCPC$, resulting in a AWI_{PHP} value lower than the sole $SHCPC$.

According to the developed model, attention was mainly devoted to the characterization of the units operation dynamics. Conversely, the demand profiles, which were ideally built as Gaussian-shaped curves distributed over time, were not characterized in terms of building typology or use and climate, but only in terms of contemporaneity. Therefore, in order to evaluate the potential changes of the units performance with a higher demand characterization, proper sensitivity analyses were carried out. More precisely, to study the dependence of the results on the boundary conditions, the effect that the most relevant influencing parameters have on results were analysed: climate and percentage of contemporaneity. Moreover, a preliminary sensitivity analysis on load intensity (either heating or cooling) is presented.

Effect of climate In line with EN 14825 standard, the climate sensitivity was developed considering the external temperature distribution of Athens and Helsinki, which are identified as "warmer" and "colder" reference climates, respectively [128]. The PHP operation modes distributions, fixed the percentage of contemporaneity equal to 52%, are reported in Figure 2.6 and Figure 2.7 for Athens and Helsinki, respectively.

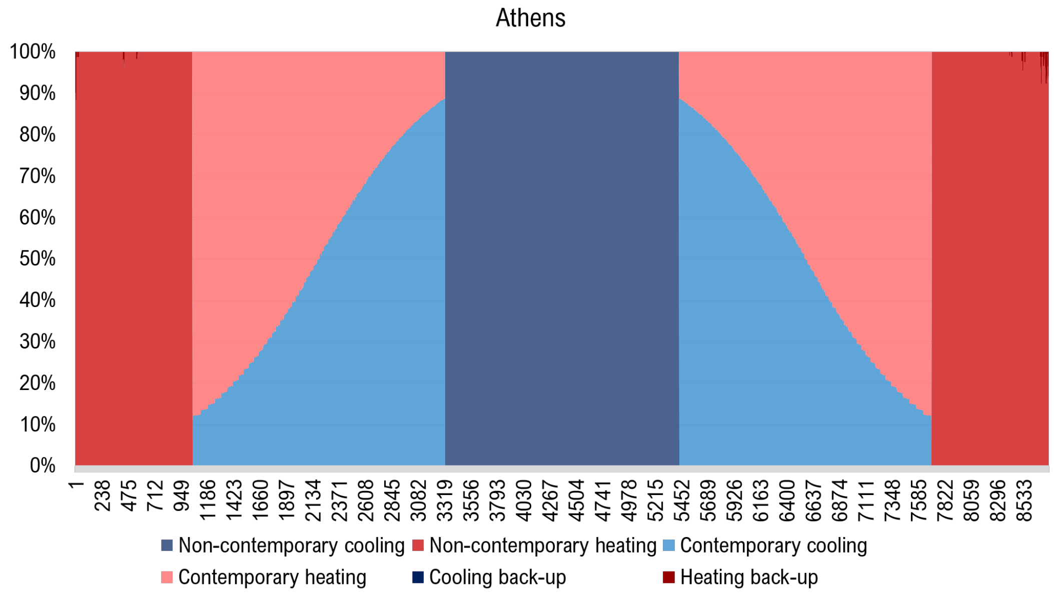


Figure 2.6: Distribution of PHP operation modes for a 52% percentage of contemporaneity in percentage terms: Athens climate.

The different conditions in terms of load distribution among the operation modes is clear. In Athens, the integration of the electric back-up system is lower than in the Strasbourg case; the situation is opposite in Helsinki, where due to more rigid climate, the back-up system is active for a higher number of hours during the non contemporary heating period. This is due to the fact that the numerical model assumes the unit not to work in case the external temperature is lower than 7°C, requesting the activation of the back-up system. These considerations are also reflected in the computed component-level KPIs, which values are summarized in Table 2.5, compared to Strasbourg results.

Table 2.5: Sensitivity analysis on component-level KPIs for PHP: effect of climate.

Climate	$CPnC$	$HPnC$	CPC	HPC	$SHCPC$
Athens	4.211	3.478	4.495	3.452	8.236
Strasbourg	4.700	2.838	4.698	3.083	8.236
Helsinki	4.905	2.003	4.889	2.828	8.236

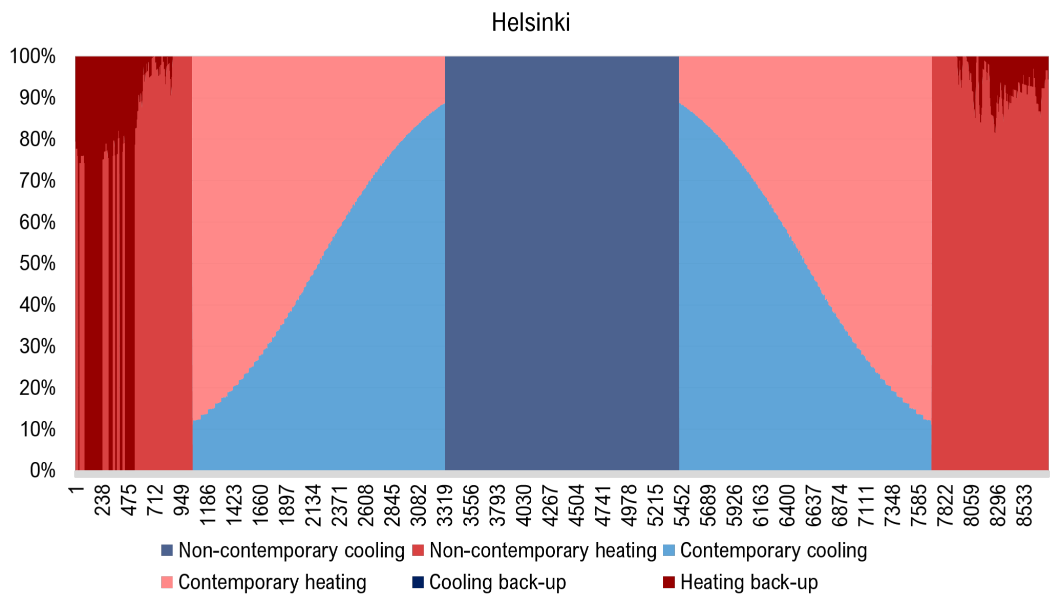


Figure 2.7: Distribution of PHP operation modes for a 52% percentage of contemporaneity in percentage terms: Helsinki climate.

A3 performances (both in terms of $HPnC$ and HPC) are better in Athens, where the external temperatures are higher during the winter season; on the other hand, the lowest values are reached in Helsinki. In the latter location, $HPnC$ value is further penalized by the additional electricity consumption of the integrative back-up system, which is assumed to be accounted in the component-level KPIs. An opposite situation is experienced when considering A1 performances; indeed, the warmer the climate, the lower the indicator is. This condition, for both heating and cooling operations, is due to the fact that the unit is usually characterized by better coefficients of performance at the intermediate partial load conditions. For this reason, the more the unit is requested to work close to full load conditions, the lower the coefficients of performance are. As for the A2 efficiency ($SHCPC$), from Table 2.5 it is clear that the KPI is not affected by the external climate. This is due to the fact that, as mentioned before, in A2 mode, the unit behaves as a water-to-water unit, with no direct contact with the external source, which is not influencing the unit performance. $SHCPC$ is only affected by the contemporaneity characterization (and thus on how the profiles are coupled), which are identical for the three climates in this sensitivity analysis.

Finally, when shifting the attention to the annual performance, some variations in terms of AWI_{PHP} indicator can be highlighted. Indeed, the indicator is influenced by the specific metrics, in each climate conditions, being a weighted average of the five component-level KPIs. However, as described in the methodological section, the weighting coefficients are dependent on the hours distribution among the operation modes, which is not affected by the external climate; therefore, the weighting coefficients are identical for the three cases. Being the $SHCPC$ equal in the three conditions, AWI_{PHP} value is solely dependent on A3 and A1 performance metrics. AWI_{PHP} results equal to 5.17, 5.12 and 4.97 for Athens (warmer climate), Strasbourg (average climate) and Helsinki (colder climate), respectively; the results are almost balanced, showing a slight increment of the weighted indicator from colder to warmer climates.

Effect of contemporaneity The PHPs potentiality is higher when the contemporary demand of heating and cooling grows. To study the effect that contemporaneity has on the performances of the unit, bundles of Gaussian pairs were created to evaluate different stages of contemporaneity, varying the standard deviation of the curve, by step of 50. In this way, 16 pairs of Gaussian normalized curves were obtained, leading to a percentage of contemporaneity ranging from 13% up to 86% [115, 127]. Figure 2.8 shows the whole set of bundles of Gaussian profiles for the different percentages of contemporaneity.

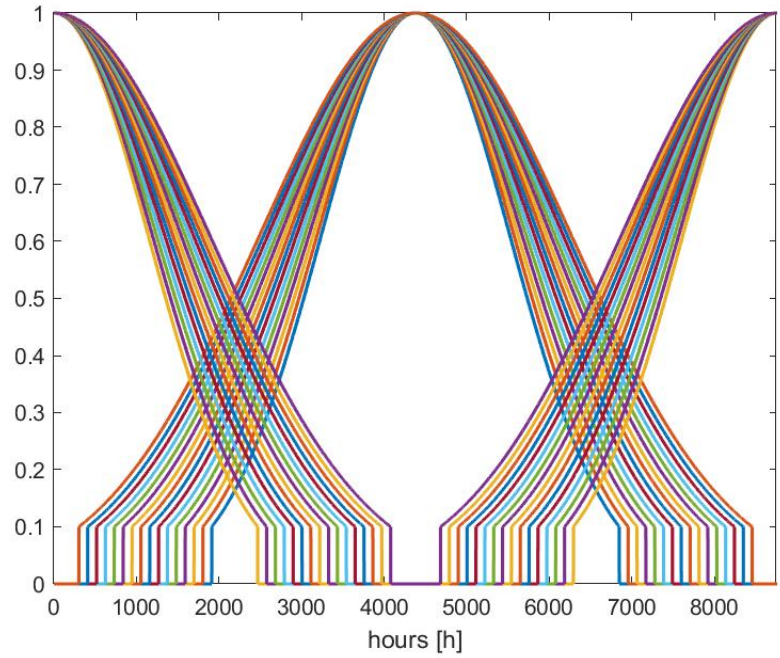


Figure 2.8: Bundles of Gaussian load curves for percentages of contemporaneity ranging from 13% up to 86% (curtailment imposed below 0.1).

Starting from this, three ranges of contemporaneity were considered: i) low contemporaneity, ranging between 13% and 37%; ii) medium contemporaneity, ranging between 42% and 62%; and iii) high contemporaneity, ranging between 67% and

86%. Based on this definition, three values of percentage of contemporaneity were defined, in order to express the average condition of each range: 23%, 52% and 76%. Table 2.6 shows the variation of the component-level KPIs as a consequence of the contemporaneity, while AWI_{PHP} values are summarized in Figure 2.9.

Table 2.6: Sensitivity analysis on component-level KPIs for PHP for Strasbourg: effect of contemporaneity.

Contemporaneity	$CPnC$	$HPnC$	CPC	HPC	$SHCPC$
23%	4.686	2.960	4.526	2.650	8.073
52%	4.700	2.838	4.698	3.083	8.236
76%	4.757	2.625	4.637	3.125	8.238

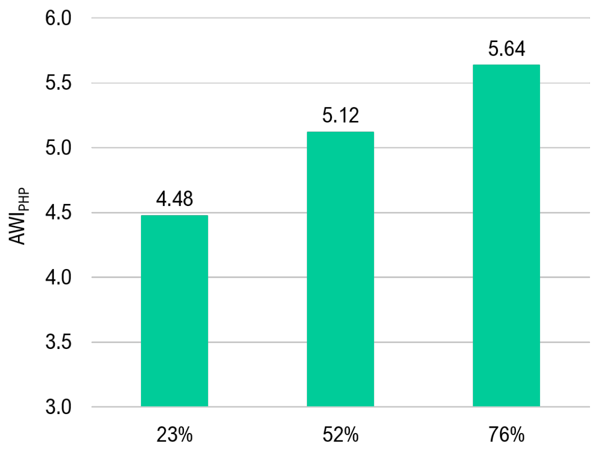
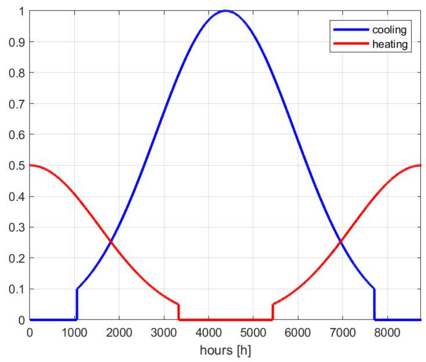


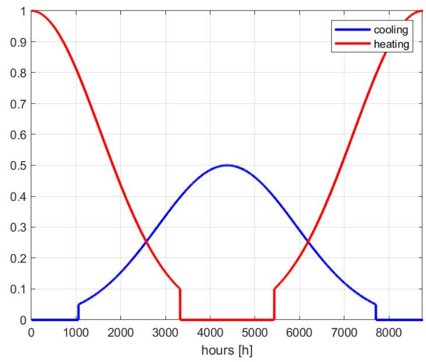
Figure 2.9: Sensitivity analysis on AWI_{PHP} for Strasbourg: effect of contemporaneity.

The component-level KPIs variations are not significant (+2% in $SHCPC$, $CPnC$ and CPC between low and high contemporaneity; -11% for $HPnC$; and +18% for HPC). This is due to the fact that these metrics are strongly correlated to external temperatures and partial load conditions, rather than on the value of contemporaneity. Indeed, the increase of the percentage of contemporaneity induces an increase of the requested loads during H_{cont}, as well as an increase of the electricity consumed to meet this load. Both increments are almost proportional, with variations depending on the units operations. Conversely, as expected, the aggregate indicator increases with the increment of the percentage of contemporaneity, since the weight of the contemporary metrics increase, giving more value to $SHCPC$, which is the highest efficiency. AWI_{PHP} increases by 14% and 26% passing from low to medium contemporaneity and from medium to high contemporaneity, respectively.

Effect of load intensity The ideal Gaussian load profiles were created assuming similar load intensities, with curves varying between 0 and 1 for both heating and cooling requests. In order to evaluate the variation of the KPIs for different conditions of heating and cooling curves coupling, a preliminary sensitivity analysis was performed also considering variable load intensities. Specifically, two variations were assumed for the 52% of percentage of contemporaneity, varying one service and keeping the other fixed, as shown in Figure 2.10.



(a) 100%cooling & 50%heating



(b) 50%cooling & 100%heating

Figure 2.10: Preliminary variations of cooling load intensity (curtailment imposed below 0.1).

The associated component-level KPIs are reported in Table 2.7, showing them in comparison with the original case of 100%cooling & 100%heating (see Figure 2.3).

Table 2.7: Sensitivity analysis on component-level KPIs for PHP for Strasbourg: effect of load intensity.

Load intensity	$CPnC$	$HPnC$	CPC	HPC	$SHCPC$
100%c & 100%h	4.700	2.838	4.698	3.083	8.236
100%c & 50%h	4.700	3.086	4.701	2.575	8.077
50%c & 100%h	4.769	2.838	4.448	3.135	8.101

According to the obtained results, it is clear that $CPnC$ and $HPnC$ values are strongly dependent on the specific performance coefficients at the different partial load conditions. The lowering of the curves allows to increase $HPnC$ for the case with reduced heating load (100%cooling & 50%heating) and $CPnC$ for the case with reduced cooling load (50%cooling & 100%heating). The performances during contemporaneity hours, indeed, are more stable, even though decrements of HPC and CPC values are measured in case the associated curves are lowered (100%cooling & 50%heating and 50%cooling & 100%heating, respectively). The

$SHCPC$, however, is higher in the cases in which heating and cooling profiles are comparable in absolute value (100%cooling & 100%heating).

Regarding the annual performance, the associated AWI_{PHP} values result equal to 5.15 for the 100%cooling & 50%heating case and equal to 4.95 for the 50%cooling & 100%heating case (both compared to the 5.12 value for the original pair of load curves). Due to the different coupling of heating and cooling profiles, the specific weighting coefficients are slightly different from the original case. The highest result in terms of annual index is the 100%cooling & 50%heating condition, according to which the lowest indicator (HPC) is associated to the lowest weighting coefficients (for only 362 hours in the year there is the need for $A3_{cont}$ integration) and, hence, its weight on the overall AWI_{PHP} decreases, advantaging the other higher coefficients.

Besides the numerical results, this activity is interesting since it allowed to differentiate the Gaussian-shaped theoretical profiles, better characterizing them according to load intensity and percentage of contemporaneity. By coupling these two information, it may be possible to create differentiated reference load curves, which may be representative of real profiles (i.e. load archetypes). Each archetype, indeed, would be characterized by a specific load intensity (both cooling and heating) and a fixed percentage of contemporaneity. This will make them more appropriate for generalizing the real profiles of different building categories, and thus to enlarge the field of application of this methodological framework.

Comparison of HVAC configurations through multi-dimensional component- and system-level KPIs

The four selected all-electric HVAC configurations were compared according to the set of multi-dimensional component- and system-level KPIs previously discussed (see Table 2.2). The same numerical model was deployed for all the configurations, which are all compared for a 52% percentage of contemporaneity and for the Strasbourg climate. Heating and cooling demands are identical for all configurations, while electricity consumptions are strictly dependent on the efficiencies of the exploited units. Table 2.8 summarizes the annual electricity consumptions of each configuration, showing also the associated annual CO_2 emissions generated.

Table 2.8: Annual electricity consumption and carbon dioxide emissions for the four HVAC configurations.

	C1	**C2**	**C3**	**C4**
Electricity consumption $[kWh/y]$	2'082'468	1'271'988	1'265'775	1'127'063
CO_2 emissions $[t_{CO_2}/y]$	874.6	534.2	531.6	473.4

Starting from the KPIs belonging to the energy/technical sphere, the main results are reported in Table 2.9.

Table 2.9: Energy-technical KPIs for the four HVAC configurations.

KPI	**C1**	**C2**	**C3**	**C4**
$CPnC$	4.789	4.789	4.789	4.700
$HPnC$	2.922	2.922	2.922	2.838
ACI	1.643	3.913	3.954	5.410
$NSLP$	50.4%	49.6%	27.1%	-

The first two KPIs ($CPnC$ and $HPnC$) are calculated for all the configurations as the ratio between heating or cooling requests and the associated electricity consumptions, only during the non-contemporaneity hours. As previously mentioned, the energy requests are identical for all the configurations. Moreover, in the case of configurations 1, 2 and 3, the same reversible HP is used to satisfy non contemporary heating and cooling requests. For this reason, $CPnC$ and $HPnC$ values are identical for C1, C2 and C3. Comparing these metrics with the PHP, it is possible to see that its performances in heating only and cooling only non contemporary modes are lower with respect to those of the reversible HP. This is due to the fact that the COPs and EERs of the PHP are slightly lower (for A1 and A3 mode), privileging the efficiency in contemporary operation mode (as visible from the previous analysis on the PHP efficiencies) [116].

Concerning the contemporaneity efficiency, the ACI index can be calculated for all HVAC configurations, even if some differences arise in case the contemporary needs are satisfied using a single component (C4) or with a multi-unit system (C1, C2 and C3). Numerically, a high ACI corresponds to a high contemporaneity efficiency. As expected, the PHP (C4) performs better compared to the other solutions (reaching a value of 5.410), while C1 represents the worst option. Clearly, the explanation resides in the fact that this configuration makes use of an electric boiler in order to meet the entire contemporary heating, which is characterized by a lower efficiency with respect to the other equipment used as integrative units. As for C2 and C3, intermediate results are achieved, with a slightly higher performance for the C3 solution, which performs an ideal optimization control between the two units (primary and secondary reversible HP), according to which the primary HP works by always satisfying the highest load (heating or cooling, depending on the hour) [116].

Finally, the $NSLP$ indicator was calculated for C1, C2 and C3, showing a decreasing trend from C1 to C3. In line with the previous analyses, C1 and C2 have a similar concept; more precisely, in these configurations, the primary reversible HP is used to cover only one contemporary service (cooling in C1 and heating in C2), independently on the intensity of the loads. Therefore, the electric boiler and the chiller are used as integration units in order to cover the remaining loads (contemporary heating and cooling, respectively), which values are numerically similar, according to the Gaussian theoretical profiles, and high. This results in close $NSLP$ values between these configurations. Differently, as mentioned, C3 is able to optimize the operations between the units, allowing the primary HP to work by priority, shifting between A1 and A3 operation to meet the highest load; this assumption helps reducing the quota of contemporary load that will request an integrative unit to be satisfied. As a consequence, the $NSLP$ value of the third configuration is lower than C1 and C2 [116].

Two annual energy KPIs (TPC and AWI) were computed in order to compare the overall performance of the configurations over an entire year of evaluation, as shown in Figure 2.11. Both indicators have trends similar to ACI index. Indeed,

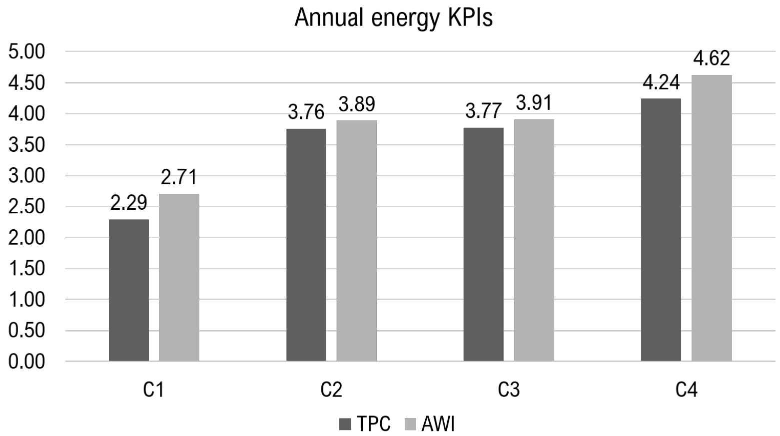


Figure 2.11: TPC and AWI results for the four HVAC configurations.

as visible in Table 2.9, all configurations have similar performances when working in heating only and cooling only modes during non-contemporaneity hours (as expressed by $CPnC$ and $HPnC$ metrics). Therefore, the annual efficiency is strongly dependent on the contemporaneity performance (also considering that H_{cont} represents 52% of the total annual hours). In line with this, the highest TPC and AWI values are reached by the PHP, obtaining values of 4.24 and 4.62, respectively; moving from C1 (worst performance) to C4, TPC increases of 85% and AWI of 71%. The difference between these two indicators is related to the weighting procedure used for the AWI computation, according to which $CPnC$, $HPnC$ and ACI metrics are weighted on the hours. Figure 2.12 shows the hours associated to the three metrics (named as hours of service provision); barred bars are used to indicate that the contemporary heating and cooling is provided by more units in parallel (C1, C2 and C3). However, in order to better tackle the differences between the configurations, a distribution in terms of units operation hours for the different configurations is reported in Figure 2.13. From this representation, it is possible to visualize the contribution of the single units within the multi-units configurations (with the first bar always indicating the primary reversible HP - Unit 1).

The annual aggregate indicator AWI needs to be distinct from the former

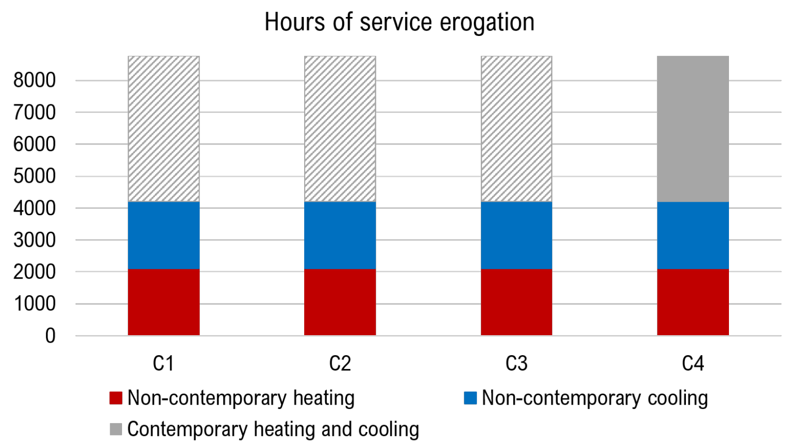


Figure 2.12: Hours of service provision for the four HVAC configurations.

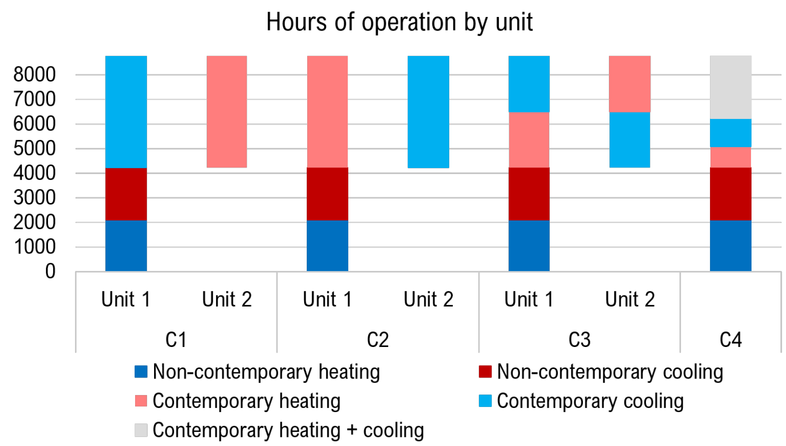


Figure 2.13: Hours of operation by unit for the four HVAC configurations.

AWI_{PHP}. Indeed, in the previous analysis, the hourly distribution among the five operation modes for the PHP allowed to calculate an aggregate index by weighting each of the five component-level KPIs reported in Table 2.4; in this way, a AWI_{PHP} value of 5.12 was obtained. Here, instead, the AWI for all the HVAC configurations, including the PHP, is calculated weighting the ACI index, thus obtaining a lower value, equal to 4.62, as shown in Figure 2.11.

Finally, deepening the financial aspects, PHP was compared with the other HVAC configurations in terms of differential variations of investment ($\Delta C_I\%$) and energy costs ($\Delta C_e\%$). Results are shown in Figure 2.14, where a negative value (for both metrics) represents a higher convenience of the PHP, while a positive value indicates that the compared HVAC configuration is still more economically attractive than the PHP [116].

Starting from $\Delta C_I\%$, all configurations have a negative percentage value, with

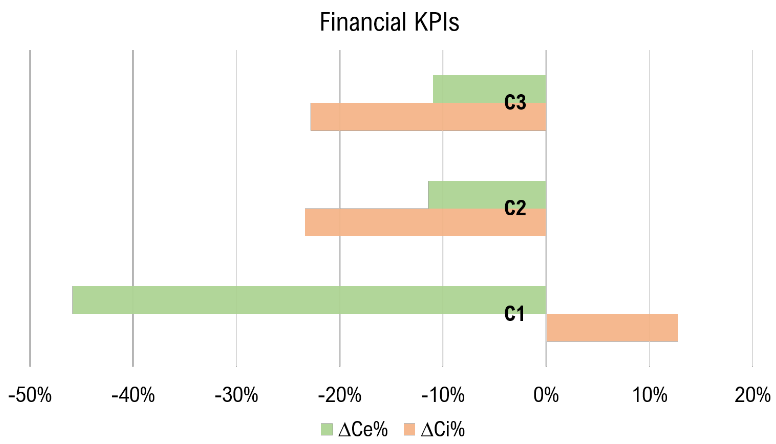


Figure 2.14: $\Delta C_I\%$ and $\Delta C_e\%$ comparison for the configurations C1, C2 and C3, with respect to C4 (PHP).

the sole exception of C1 (+12.8%). Indeed, due to the wider market diffusion of the electric boiler, its investment cost is significantly lower than the market price of the other units. Conversely, C2 and C3 are composed by two expensive solutions (HP + chiller, HP + HP), and, thus, both configurations present an investment cost approximately 23% higher than the sole PHP. Instead, when looking at the energy expenditure, for all configurations the obtained $\Delta C_e\%$ values are negative, meaning that the PHP represents the most financially advantageous solution from the operation standpoint. In this case, the worst configuration is represented by C1, which is characterized by a high electricity consumption due to the use of the electric boiler. Again, C2 and C3 have similar behaviours, showing a energy cost increment of approximately 11% compared to the PHP.

So far, the comparison of the HVAC configurations was performed by means of KPIs assessed separately and alone, without analysing any possible trade-off between the different perspective. For this reason, the final part of this section move the lens from a single- to a multi-perspective standpoint [116]. Figure 2.15 was designed in order to provide a snapshot of the compared technological solutions, integrating all the three dimensions that were previously assessed. In particular, each dimension (energy/technical, financial, environmental) is represented using a proper KPI: ACI, investment cost and annual CO_2 emissions. More precisely, the bubble plot of Figure 2.15 reports environmental and financial dimensions on x- and y-axes, respectively, while the size of the bubble is used to indicate the technical dimension, in terms of contemporaneity efficiency (ACI metric) [116]. According to the bubbles positioning into the x-y space, the best solutions are located in the bottom-left part (lower emissions and investment costs), while the worst performing ones are in the top-right part of the graph. However, in order to better reflect the technical capabilities of the configurations in meeting the energy demands,

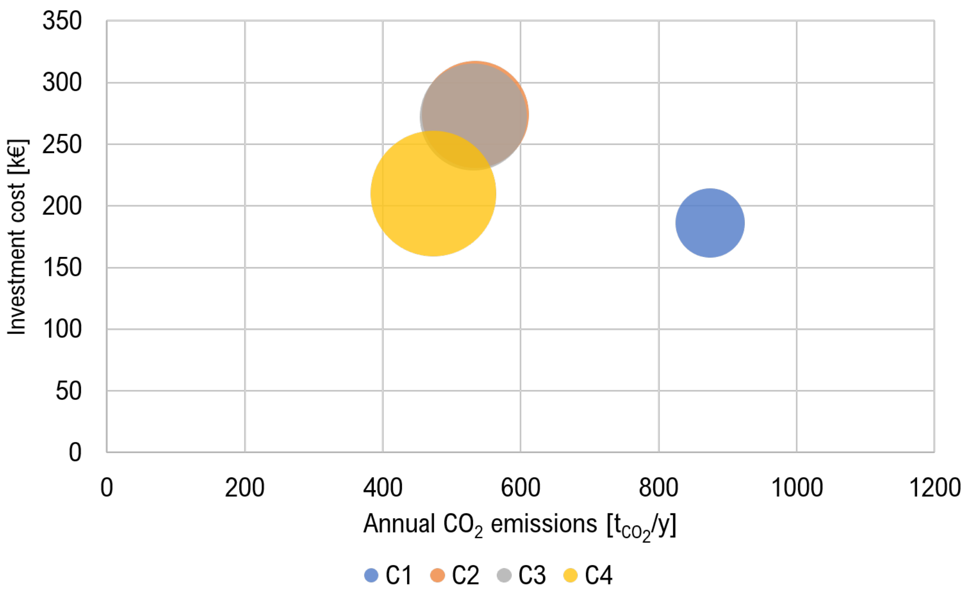


Figure 2.15: Multi-perspective bubble graph for comparing the four HVAC configurations (the size of the bubbles represents the value of the ACI index of each configuration).

efficiency needs to be accounted. In particular, the peculiarity of contemporary needs guaranteeing that was addressed in this section pushed towards the adoption of ACI as relevant KPI for the energy/technical dimension. Therefore, in addition to the previous assessment, the configurations are better judged when having a high ACI (larger bubble dimension).

Looking at Figure 2.15, it results that C1 is characterized by the lowest investment cost; however, even if it could be the most financially attractive solution for a private investor, it should be noted that it represents the worst conditions in both environmental and technical terms. C2 and C3, instead, are characterized by relatively high ACI values and low emissions, but they present the highest investment costs compared to the other alternatives. Finally, C4 is characterized at the same time by the highest contemporaneity performance and the lowest CO_2 emissions, and has a low investment cost, comparable to C1. As reported in Ref. [116], from the graph, no configuration emerges as the most performing in all the considered dimensions, even though it is clear that the PHP represents the best compromise between the different perspectives.

2.1.6 Conclusions and further investigation

The transition of the building sector will depend on the improvement of the energy efficiency of its components, and thus will be strongly connected to the use of efficient and sustainable HVAC systems, which will need to face the expected changes in future buildings energy demands. In particular, the progressive temperature increment due to climate change will lead to an increase of buildings cooling needs and a progressive overlap of heating and cooling loads. In this section, attention was mainly devoted to electric solutions, thanks to their high energy efficiency and low environmental impact, if coupled with renewable energy sources. Among them, reversible heat pumps and polyvalent heat pumps are gaining interest. The polyvalent units, moreover, even if less diffused than traditional heat pumps, present several benefits, thanks to their capability of matching cooling and heating loads simultaneously and independently.

However, still few efforts have been dedicated in literature to model their operations and to valorize them over competing alternatives using proper performance indicators. Therefore, this section aimed to present a simplified numerical model to assess and simulate the PHPs operation dynamics. Morevoer, attention was devoted to the definition of a set of KPIs, able to value their performances and to compare their operations with other multi-units HVAC configurations. From the energy standpoint, PHPs intrinsically allow to simultaneously meet cooling and heating needs, thus guaranteeing higher flexibility and versatility with respect to other all-electric HVAC configurations, which will request the integration of more units working in parallel to provide the same services [116]. The comparative analysis allowed to drawn some interesting considerations on the potentialities of the PHPs, which can represent a good balance between technical, financial and environmental aspects. Indeed, thanks to the development of the graphical multi-perspective tool, it was possible to investigate how, even though PHP is not the solution with the lowest investment cost, among the considered alternatives, it can be beneficial both in environmental (lower CO_2 emissions) and energy terms (high contemporary efficiency). Moreover, the possibility of using a single unit to provide the different services can be beneficial also in terms of system complexity and maintenance over the years. Even though only few configurations were compared, this analysis allowed to pinpoint the need for multi-dimensional instruments, when assessing and comparing different technological options. Indeed, despite consumers' or investors' choices are still mostly driven by financial convenience and attractiveness, this dimension is no longer enough. New and effective decision-making support tools (as Figure 2.15) are needed in order to better visualize the trade-offs between different alternatives, and to translate technical information in forms comprehensible by a broader audience. In particular, as will be addressed in the next section, this scientific effort can force policy makers to act and develop ad-hoc strategies, aiming to translate the benefits of still more expensive but environmental-friendly solutions into financial terms, driving their future diffusion and adoption.

Despite the interesting outcomes of the work, it still presents some limitations, which open the way to future investigation. Indeed, in order to better capture the real operation modes of the units, further work will be dedicated to refine the preliminary numerical model and to test it with different machines, with diverse characteristics (among which, for instance, the presence of inverters). Moreover, the load profiles are currently defined based on the time variable, thus stressing the relevance of the contemporaneity hours in the modelling of the PHPs operations, being it currently not accounted in normative contexts. However, the analysis stressed the importance of the theme of load profiles, in order to study the application of appropriate machines for satisfying the demand characteristics. Therefore, further work will be devoted to test the numerical model built based on the Gaussian-shaped ideal profiles with real load profiles, coming from monitoring campaigns or from energy simulations, in order to investigate the validity of the model also in case of real demand characteristics (mainly non-residential), analysing the potentialities of polyvalent heat pumps to match the load of these building categories. This step could be propaedeutic to define and build representative load profiles, tailored on external temperature variations and with fixed contemporaneity conditions (dependent on the building characteristics). This further investigation could allow to couple the performed unit characterization with a more detailed demand representation, coupling both temperature and time (i.e. contemporaneity) constraints. Finally, due to the current commercial interest in defining standardized metrics for the polyvalent heat pumps, the developed component-based KPIs could be used for guiding and supporting the development of new standards, more tailored on the PHP technology, especially in relation with the contemporaneity issue, which is still not accounted in existing standards.

2.2 Indicators to value technologies for policy-oriented purposes

2.2.1 Overview

In the view of a science-based decision-making, the use of KPIs is particularly diffused to guide and support the evolution and planning of future strategies for building renovation, as well as to inform and communicate the associated benefits also to a non-expert audience. Building-level KPIs can be used as tools to support the energy planning process, to give a snapshot of the current performance of individual buildings, as well as to study the capacity of ad-hoc policy measures in varying the competitiveness of alternative retrofit options, and thus in driving consumers' choices towards more environmental-friendly solutions. In line with the above, this work aims to identify a set of KPIs able to study buildings from a multiple perspective, highlighting and coupling their financial and environmental performances, as well as to assess possible renovation strategies according to the existing trade-off between these perspectives. The study aims to propose the use of proper and effective decision support tools (either graphical or analytical) to help decision-makers in comparing the performances of building retrofit alternatives and in forecasting the potential effect of different policy-based actions on their favourability. The methodology is exemplified for the Italian residential sector, analysing the competitiveness of diverse technological alternatives for the substitution of the existing heating systems, through the definition and use of simple and aggregate multi-dimensional KPIs. The analysis makes use of the reference building approach to characterize demands conditions and to identify the effect of climate, thermal properties and building typologies on the reciprocal competitiveness of the technologies. In order to support future policy decision-making in setting appropriate measures to value more environmental-friendly solutions, translating their environmental benefits into financial terms, the analysis is conducted for 2030 and 2050, aiming to propose a medium- and long-term instrument for supporting future renovation strategies for the sector.

Keywords Residential building sector, widespread technologies for space heating, Key Performance Indicators, decision-making support, usable knowledge, reference building approach.

Declaration Part of the topics described in this chapter were previously published in the following publications:

- E. Bompard et al., *Electrify Italy*, Fondazione Centro Studi Enel, 2020 [46].
- **G. Crespi**, E. Bompard, *Drivers of energy transition of Italian residential sector*, REHVA Journal 57, pp. 6-10, 2020 [131].

The contents of this section will be submitted to "*Technological forecasting and social science*" journal (G. Crespi, I. Abbà, G. Vergerio, C. Becchio, S.P. Corgnati, "*Key Performance Indicators for decision support in building retrofit planning: an Italian case study*").

2.2.2 Background

Buildings are recognized to be optimal agents in the energy transition [132], which, to occur, asks an unprecedented effort to policy makers, stakeholders and individuals. Effectively planning the evolution of the sector and pushing the market towards the adoption of low-carbon technologies is of paramount importance.

In this framework, the use of KPIs has proven to be particularly beneficial for the building sector, since, according to literature, they represent the most suitable approach for combining "energy efficiency improvement and policy evaluation" [133]. Indeed, KPIs are commonly developed and used for assessing and measuring the performances of single technologies and buildings, as well as for supporting the development of energy policies for improving the energy performance of buildings, using them as policy making tools [134]. The former purpose has been discussed in the previous section, in which ad-hoc KPIs were developed in order to reflect commercial stakeholders' interests in assessing the performances of a particular technology (i.e. polyvalent heat pump), to value its benefits in terms of technical performance, and to compare it with other HVAC configurations, in terms of capability and efficiency of heating and cooling services provision. Besides the interest in developing specific performance indicators for the PHP unit, the definition of the multi-perspective graphical tool (see Figure 2.15), able to combine technical, environmental and financial domains, has stressed a new perspective; indeed, the analysis has highlighted the need to shift from a single dimension (technical) to a multi-dimensional standpoint, when evaluating and comparing different strategies or technologies. This consideration is central in this section, in which KPIs are exploited for policy-oriented purposes, to be used as effective tools to help policy decision-makers in setting and monitoring the potential effects of their strategies in the medium- and long-term, when considering and comparing potential renovation strategies for residential HVAC systems.

In literature, renovation projects and strategies are commonly evaluated and compared according to a multi-dimensional standpoint, usually performing a whole-building-level analysis [117]. Indeed, according to Jafari et al., the identification of the most suitable retrofit option for individual buildings is intrinsically a multi-objective optimization problem, with different criteria entering into the decisional process [135]. However, criteria are usually considered alone or in combination with other KPIs, depending on the perspective of the stakeholder involved in the decision context [135]. Proper KPIs must be selected in order to express stakeholders' perspectives and objectives and should be able to capture the multiple benefits of the retrofit options. Moreover, besides the identification of multi-objective functions, a step forward is needed, aiming to develop KPIs able to integrate conflicting viewpoints, as well as to identify the possible trade-offs among the various dimensions [136, 137]. Indeed, typically, renovation strategies are evaluated according to the private investor/decision-maker perspective, whose needs and interests are clearly different from others. Keeping an eye on the technological comparison for the building sector, for instance, private and public objectives usually differ. Indeed, if from one side private investors' choices are still mainly guided by financial attractiveness, new interests and objectives are spreading, mainly at policy scale, aiming to push the market towards more environmental-friendly solutions, in order to respond to the ambitious efforts requested to the building sector to reduce its impact over time [131].

For this reason, KPIs must respond to the need of combining also opposite or conflicting perspectives, and to increase the awareness on the multiple benefits of the alternative retrofit options. Indeed, it is important for policy discussion to prioritize renovation measures representing the best compromise between costs and benefits, including those going beyond the purely financial convenience [54]. To accomplish this, policy makers should promote more environmental-friendly retrofit solutions, developing proper policy measures able to reduce the still existing gap between "green and profitable investments" [138]. Still, retrofit measures guaranteeing high emission savings are usually not financially attractive for the private investors, due to their high associated financial risks or returns of the investment [138, 139, 140]. This consideration is also in line with Geels, who stated how the most sustainable solutions usually are less performant in financial terms with respect to more traditional technologies, thus highlighting that, for the sustainable transition to happen, "changes in economic frame conditions" are requested [33].

To accomplish this, effective policy tools are needed. According to Bergek et al., such instruments can be classified in "economic (CO_2 taxes, emission trading), general regulatory (emission regulation), technology-specific economic (subsidies for specific technologies), and technology-specific regulations" [141]. All these instruments can be used to push more environmental-friendly retrofits, by appropriately "modifying" their costs for the consumers, in order to reflect their higher environmental performance [138]. The study reported in Ref. [138] has demonstrated how the use of suitable political instruments can drive consumers' investment decisions towards more environmental-friendly solutions (i.e. thermal building retrofit), while guaranteeing a reduction of the environmental impact of the sector (i.e. thanks to the diffusion of retrofit solutions characterized by high emissions savings). In particular, three political instruments are addressed, namely environmental taxes, indirect subsidies and energy efficiency insurances, showing their different impact on the Net Present Values of the analysed retrofit solutions [138].

Similar considerations are drawn in this application, which aims to evaluate the competitiveness of alternative technological solutions for the building retrofit (i.e.

thermal generator substitution), keeping in mind what the different stakeholders involved in the renovation process might be willing to control. In particular, in order to combine the possible conflicting interests of private and public stakeholders in case of technological competitiveness, the comparison is based on the conflict between the private benefit in selecting the most financially attractive solution and the public risk associated to the environmental impact that the private choice would induce, in case the most financially convenient solution is at the same time the most environmentally risky. For combining these perspectives, a multi-domain indicator is identified, aiming to evaluate the performances of more environmental-friendly solutions in case the benefits they guarantee with respect to the most probable consumers' decision are translated into financial terms.

In line with the previous section, attention is devoted to investigate and properly value energy sources and technologies diverse from the traditional fossil-based, still widely adopted in individual buildings, focusing on the role of electric solutions for the building sector. The analysis previously discussed, however, was mainly focused on the technological characterization, rather than on the simulation or characterization of the building-specific demand conditions, which is instead relevant for this section. Indeed, to better identify the operational conditions in which alternative technologies could be installed and, thus, to evaluate the impacts of their adoption from a whole-building-level perspective, building bottom-up models are crucial [142]. According to Refs. [47, 48], indeed, retrofit strategies (i.e. installation of low-carbon HVAC technologies) should be properly defined and tailored on building characteristics, in order to identify the solutions able to meet energy needs (in turn dependent on building typology, location, period of construction etc.) in the most cost-effective way. For this reason, the simulation of proper building bottom-up models is in line with the need to further boost energy efficiency improvements and on-site renewable integration at single building level [118, 143].

Bottom-up modelling techniques are widely deployed for supporting decision-making processes and their use can be particularly beneficial for the building sector, to investigate how "various individual energy efficiency measures impact on CO_2 emission reduction, such as by replacing one type of heating systems with another" [144]. Indeed, to keep in line with the technological development the sector is experiencing [142] and to evaluate the future trends of energy demands and environmental impacts of the building portfolios [145], it is fundamental for policy decision-makers to estimate and understand the potentialities of energy and economic savings associated to specific renovation interventions or technological substitutions, in case these measures would be "applied to all buildings of similar program type, age, category, or archetype (for example, single-family homes built before 1980)" [145]. The performances of diverse retrofit measures in terms of energy or economic savings can be evaluated by "replacing "as-is" templates with new templates that reflect these upgrades" (e.g. substitution of the thermal generator, substitution of electrical equipment of lighting systems, etc.) [145].

To this purpose, archetype (or "prototype") modelling is widely recognized and deployed. This bottom-up engineering modelling approach is based on the concept of reference buildings (RBs) or archetypes, which can be used to evaluate the energy-environmental-economical performance of single buildings or groups of buildings, which are considered representative of a portion of the building stock [146, 147, 148]. According to Ref. [147], the archetype modelling can be used for different purposes. Firstly, by providing specific information on the individual buildings, it can estimate their energy performance when scaled up to the whole building stock, as well as to estimate the savings associated to different energy conservation measures to guide and support policy decision-making at different scales [147]. This element will be further discussed in Chapter 3, where attention will be devoted to the assessment of the national building stock. However, reference buildings deployment can be beneficial also according to other aspects. As reported in Ref. [147], RBs can be used: i) "by consultants for initial energy advice activities in order to provide house owners a quick overview of the energy performance of a building similar to their own"; ii) "as a set of example buildings, in software comparison studies or for the evaluation of subsidy programmes"; or iii) "as an appropriate instrument for housing companies to assess the energy performance of their building portfolio" [147].

The RB concept has been widely deployed in literature to study the current performance of the selected representative buildings, as well as to forecast the evolution of their future energy performance. The latter theme is touched in this section, in which the RB approach is used in order to characterize the demand conditions to be satisfied by alternative HVAC systems (i.e. heating generation technologies), aiming to highlight and simulate the future impacts of diverse policy measures on the competitiveness between the studied technological solutions. Indeed, as stated by Allouhi et al. [149], the modelling of "what-if" scenarios at single building level allows to identify the effects that potential future policies could have on the building stock [149]. In this section, the residential sector is in the spotlight, since, despite the energy efficiency improvements already undergone during the last decades, its potential for energy and economic savings is still largely untapped [47, 48, 49]. Residential buildings represent the biggest portion of the EU building stock [48], responsible of 26.1% of the overall final energy consumption [36] in 2018, 63.6% of which generated by space heating end-use [36], which is of interest in this section.

In the light of the above, to value and promote environmental-friendly retrofit solutions and to highlight the technological alternatives with the best trade-off between financial and environmental performances, the application aims to disclose information about widespread technological alternatives, focusing on the environmental benefits (or risks) that their adoption in the analysed reference buildings would guarantee (or generate). An effective medium- and long-term energy planning for the building sector needs to be supported by clear information on the performances of the possible technological solutions at disposal, expressed through proper policy tools, among which KPIs are certainly the most common ones. Through an analysis at RB level, the work aims to define proper decision-making tools (either graphical or analytical) in support of the policy makers, to assess the effect that some policy measures affecting the private sphere (e.g. price mechanisms, environmental taxes, incentive mechanisms) could have on the reciprocal competitiveness of the technologies under investigation in the medium- and long-term.

2.2.3 Methodology

Aiming to support decision-making in the field of building energy planning, this application allows to tailor the general methodological framework of Figure 1.8, with the scope of comparing different alternative technologies for residential buildings retrofit, identifying a set of KPIs able to assess their environmental and financial trade-offs. Starting from the definition of simple KPIs able to characterize the building technologies and to drive their diffusion, the work aims to combine them with the use of appropriate multi-dimensional analytical and graphical tools. Figure 2.16 summarizes the main methodological steps, which can be summarized as follows:

- **study: definition of relevant KPIs**. Simple indicators are identified to assess the financial and environmental performances of a set of generation technologies employed in the building sector.
- **simulate: computation of relevant KPIs**. Based on the RB approach, the performances of the technological solutions are assessed by computing the identified simple KPIs.
- **synthesize and support: graphical and analytical synthesis of results**. KPIs are graphically represented and combined, by defining an aggregate multi-dimensional indicator, named "Global Cost per Emissions Saving" (GCES).
- **simulate and support: definition and assessment of policies**. Specific policy measures are defined and assessed, aiming to evaluate their impacts on the simple KPIs and on the GCES indicator and, thus, on the competitiveness of the analysed technologies.

Study: definition of relevant KPIs

KPIs are crucial to describe and reflect the interests and objectives of the stakeholders involved in the renovation process. In particular, two different and opposite perspectives were considered. The main one is that of the policy-makers who, aiming to boost the retrofit of the existing building sector and the spreading of low-carbon

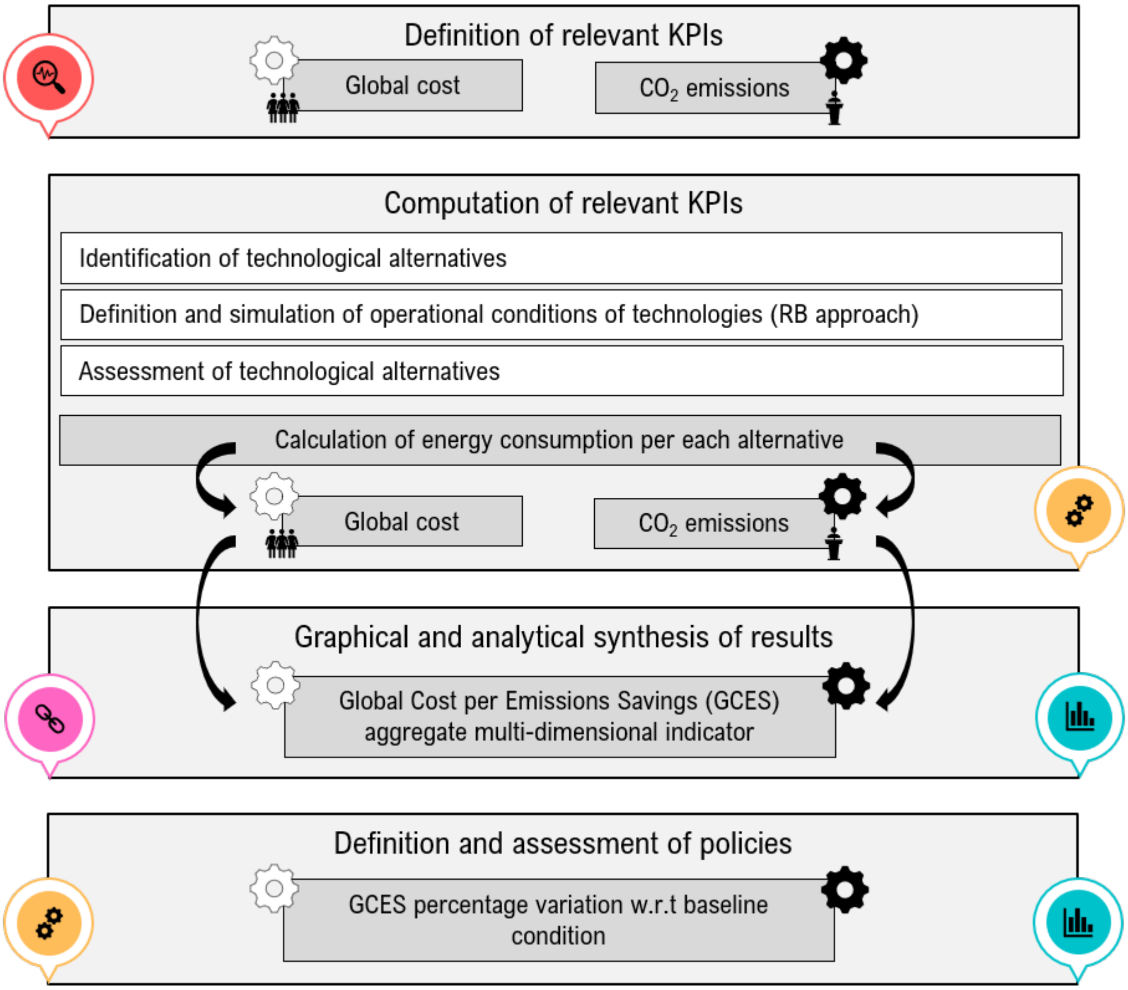


Figure 2.16: Main methodological steps.

technologies, want to have a clear picture of the guaranteed performances of the technologies at disposal. On the other side, technological spreading is still guided by the choices of private investors (i.e buildings owners and/or occupants), whose decisions are mainly driven by financial interests. Two KPIs were selected to reflect both public and private perspectives, while measuring the performances of the technologies: global cost and CO_2 emissions. The selected KPIs allow to represent, respectively, the private and public side drivers in the choice of new technologies to be deployed when a building retrofit occurs. Indeed, as reported in Ref. [131], from a private perspective, the selection of a new technology to be installed is still driven by financial convenience and attractiveness and, for this reason, the global cost was selected as an indicator of the financial performance of the considered technologies. By definition, global cost is a parameter usually used to compare different alternatives in retrofit interventions [115, 131] and it allows to estimate the financial performance of a technology over others according to a life-cycle approach, combining all the expenses borne by the building owner or occupant, thus representing a relevant benchmark for making investment decisions [131]. On the other side, bearing in mind the ambitious targets conceived for the building sector in terms of emissions reduction, in order to drive the building sector energy transition, policy makers will realistically define appropriate policy measures capable of forcing the market towards the adoption of low-carbon solutions, seeking to make them more financially attractive for the investors [131]. For this reason, CO_2 emissions were identified as a possible driver from the policy makers' standpoint.

Simulate: computation of relevant KPIs

It is clear that the adoption of a particular technology in buildings can guarantee diverse financial and environmental performances, in terms of the above-introduced KPIs. In this work, their computation passed though the following steps:

- identification of technological alternatives;
- definition and simulation of operational conditions of technologies, using the RB approach;
- assessment of the performances of the considered technologies.

Based on a market study, the most diffused technological options to be compared were selected, collecting data on their generation efficiencies and costs for their purchase and maintenance, and on their typical lifespan. Once the initial selection procedure is concluded, the context in which these technologies would operate needs to be assessed. Specifically, to estimate the energy needs that these solutions should cover, the RB approach was deployed. The RB term identifies a real or statistically determined typical building, which can be considered representative of a portion of the building stock [146, 147]. Once RBs are identified and characterized in terms of geometry, thermo-physical properties, periods of construction, and climates, through their modelling it is possible to calculate the heating needs, based on steady-state or dynamic simulations. Then, knowing the efficiencies of the installed systems, it is possible to estimate the energy performances of the alternative technologies, by computing the annual energy consumption associated to them.

Using this approach, the set of technologies previously identified and characterized can be applied to the different RBs under analysis (assuming to substitute their original thermal systems), thus resulting in diverse energy consumptions, in turn influenced by the specific characteristics of the RBs themselves. Based on these outcomes, the identified KPIs can be calculated for each alternative, according to Eq. 2.25 (elaborated from EN 15459 [150] for a single component) and Eq. 2.26.

$$C_G(t)[€] = C_I + \sum_{i=1}^{t} (C_a(i) \cdot R_d(i)) - V_{f,t} \tag{2.25}$$

$$CO_2 \left[\frac{kg_{CO_2}}{y} \right] = \sum_{z} c(z) \cdot EF_{CO_2}(z) \tag{2.26}$$

where C_I represents the initial investment cost of the technological solution under investigation, $C_a(i)$ the annual costs (including operation and maintenance) for the i_{th} year, $R_d(i)$ the discount formula for the i_{th} year, $V_{f,t}(j)$ corresponds to the final value of the component or system at the end of the calculation period t, $c(z)$ corresponds to the annual building final consumption for the z_{th} energy carrier and $EF_{CO_2}(z)$ represents the emission factor for the z_{th} energy carrier. Since the analysis focused on the retrofit of a single technological component, the period t for the calculation of the global cost was assumed equal to the useful life of the technology, and its final value was not included in the computation.

Synthesize and support: graphical and analytical synthesis of results

To visualize the reciprocal behaviour of the technologies, the results are synthesized in a graphical tool (see Figure 2.17). This representation is intended as an instru-

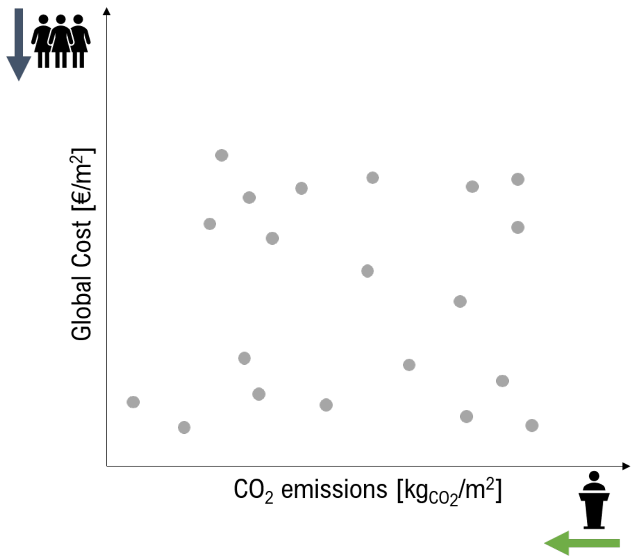


Figure 2.17: Schematization of the graphical decision support tool.

ment for the policy makers to visualize the reciprocal positioning of the considered technological solutions within the x-y space, comparing them in financial (private) and environmental (public) terms. Top-right dots represent the worst solutions for both pirvate and public stakeholders, being characterized at the same time by high emissions and costs, while the bottom-left dots represent the best solutions, able to guarantee low environmental impacts and low costs. Based on this graphical instrument, policy makers can easily identify the potential risk associated to the adoption of the technologies with the worst environmental performances. Indeed, the tool allows to visualize the alternatives with the lowest global-cost (on y-axis), which are reasonably preferred by private investors, and those with the lowest emissions (on x-axis), preferred by public stakeholders. Usually, the best solutions according to each perspective (private or public) do not coincide, and thus the highest risk for the policy makers occurs when the most affordable solutions for the private are at the same time those with the worst environmental performances.

Clearly, the reciprocal positioning of the technologies in the x-y space is strongly dependent on the RB in which they are installed. Deepening the analysis for a single RB, Figure 2.18 reports an exemplification of two cases in which three technologies (dots A, B, C in one case, dots A', B, C in the other case) can be suitable for the retrofit of its original system. In both cases, the alternatives for the same RB are characterized by comparable financial performances, while their environmental impacts are clearly different. Indeed, when comparing the first triplet of alternatives (dots A, B and C), dot A represents at the same time the most financially attractive solution and the most environmentally risky, since dots B and C are both characterized by lower emissions with respect to A (B has a slightly better environmental performance with respect to C, but against a higher global cost). Assuming that a private stakeholder would most likely choose based on financial convenience (dot A), this condition represents the highest risk for the policy maker, since it represents the situation in which a private investor would select the solution more environmentally impacting than any other potential alternative at disposal.

Conversely, this situation does not occur in case the least environmental performing solution does not coincide with the most convenient solution from a financial point of view. This is the condition represented by dot A', when the solutions for a single RB are represented by the triplet A', B and C (see Figure 2.18). Therefore, if in this latter case the policy maker would not perceive any risk for the adoption of the most financially attractive solution by the investor (dot C in Figure 2.18), conversely, in the first case (i.e. A, B, C triplet), she/he would act in order to push towards the adoption of more environmental-friendly solutions trough the use of proper policy measures.

To tackle this, an aggregate multi-dimensional indicator, named "Global Cost per Emissions Saving" (GCES) was defined. Specifically, when there is the risk of adoption from privates of the most impacting solution (as in the A, B, C triplet), GCES is computed for each more environmental-friendly alternatives with respect to it, coupling financial and environmental performances at once, aiming to study how much the other competing solutions cost compared to the benefits they may guarantee with their adoption (in place of the most impacting). Specifically, the GCES indicator is defined as the ratio between the global cost of a competing

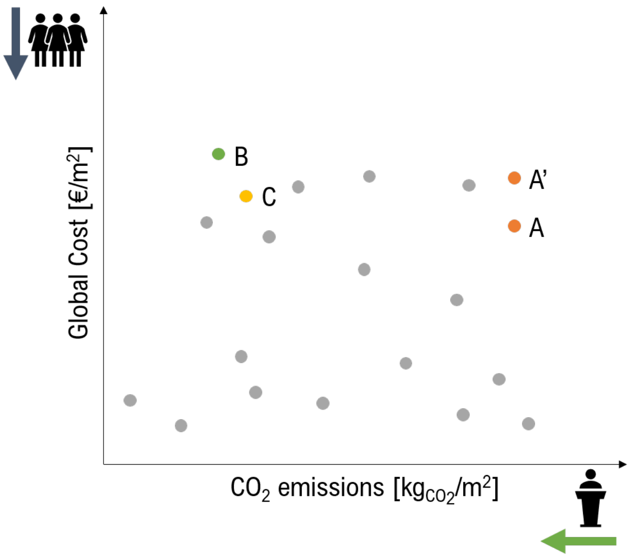


Figure 2.18: Schematization of the graphical decision support tool: the case of a specific RB.

solution and the CO_2 emissions that this solution can save with respect to the worst environmentally performing and most financially attractive one, as in Eq. 2.27.

$$GCES(j)\left[\frac{€}{kg_{CO_2}}\right] = \frac{C_G(t,j)}{CO_{2,worst} - CO_2(j)} \tag{2.27}$$

where $C_G(t,j)$ represents the global cost of the j_{th} solution among the set of better environmental performing ones, $CO_{2,worst}$ represents the emissions of the worst environmental performing (but most financially attractive) solution for the specific RB under investigation and $CO_2(j)$ the emissions of the j_{th} solution.

According to this vision (see Figure 2.18), considering the first example of technologies potentially applied to a specific RB (dots A, B, C), dot A would be selected as the worst performing in terms of CO_2 emissions, and thus identified as the benchmark for the assessment of the emissions savings that the adoption of the other alternative solutions could guarantee. The GCES would be then calculated for solutions B and C, as reported in Eq. 2.28 and 2.29.

$$GCES_B\left[\frac{€}{kg_{CO_2}}\right] = \frac{C_G(t)_B}{CO_{2,A} - CO_{2,B}} \tag{2.28}$$

$$GCES_C\left[\frac{€}{kg_{CO_2}}\right] = \frac{C_G(t)_C}{CO_{2,A} - CO_{2,C}} \tag{2.29}$$

It is important to mention that this assessment is performed only for the RBs which behaviour is exemplified by the case of the A, B, C triplet. Conversely, in case, for a specific RB, the solution with the lowest global cost is among the set of more environmental-friendly solutions (as it happens with dots A', B and C), GCES is not computed, being A' (i.e. the riskiest in environmental terms) already excluded.

Simulate and support: definition and assessment of policies

As previously stated, the indicator is not used to identify investors' choices in case of retrofit, but it is designed as a tool in the hand of policy makers, for supporting the definition of appropriate future policy strategies, aiming to reduce the GCES of the low-carbon technologies, for pushing the market towards their adoption.

In line with this, the research aimed to explore in which directions the market and the policy context might drive private choices, by investigating how innovative policy measures can affect the global costs of more environmental-friendly solutions. To this purpose, different policy scenarios were investigated, in order to assess the effects of the considered policy strategies on the GCES aggregate indicators, evaluated in terms of percentage variations of the GCES for each environmental-friendly solution induced by a specific policy scenario. This analysis can be helpful for policy makers to forecast how different policies might affect the reciprocal competitiveness of the technological solutions at disposal in a medium- and long-term time horizon.

2.2.4 Case study

The methodology was applied to Italian residential buildings, focusing on the space heating service. In EU, space heating is still dominated by fossil fuels, with gas as the major contributor, representing 42.9% of the final energy consumption of the sector in 2018 [36]. The Italian situation reflects the cited EU data; in 2018, gas represented 58.4% of the final consumption, while renewable and wastes (including electricity-based RES and biomass) covered 28.3% of the energy consumption [36].

The research aimed to develop a policy decision-making support tool for studying the competitiveness of the technologies on a mid- and long-term timespan; for this reason, the KPIs were computed for 2030 and 2050, in order to provide a forecast of the reciprocal convenience of different thermal generators for space heating in residential buildings with a baseline trajectory and different policy scenarios. The methodology was tested considering three technological alternatives: condensing gas boiler, biomass boiler and electric air-to-water heat pump. The choice derived from a review of the most diffused retrofit options in Italy; indeed, based on data regarding the main interventions incentivized through Ecobonus mechanism, in 2018, these three technologies represented around 90% of total Ecobonus interventions for winter air conditioning, with condensing gas boilers and heat pumps representing the most diffused ones (67% and 22%, respectively) [151].

For each technology, generation efficiencies were assumed based on the requirements for the incentive mechanism of *Conto Termico 2.0* [152], as summarized in Table 2.10.

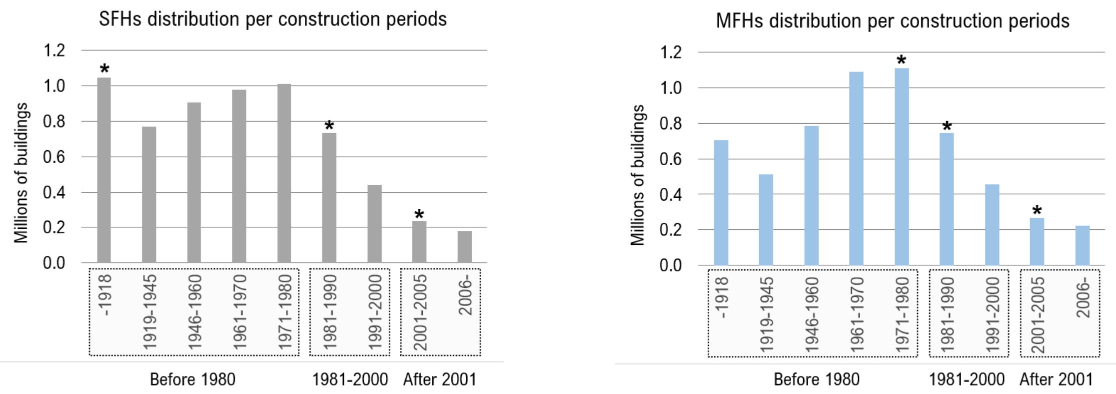
Table 2.10: Assumed generation efficiencies of the considered technologies.

Technology	Generation efficiency
Condensing gas boiler	0.96
Biomass boiler	0.88 - 0.89
Electric air-to-water heat pump	3.80 - 4.10

In order to compute the energy consumptions related to the use of these technologies, the RB approach was adopted. RBs were defined based on the outcomes of the "Typology Approach for Building Stock Energy Assessment" (TABULA) European project [146, 147]. In this application, starting from TABULA database for Italian archetypes [153], the RBs were identified in terms of geometry, envelope and system characteristics. A preliminary analysis of the Italian residential stock was performed, classifying it into single-family houses (SFHs) and multi-family houses (MFHs) (i.e. buildings with two or more apartments). Buildings were further subdivided into nine construction periods, assumed from the last Italian census [154], as depicted in Figure 2.19. Three macro-classes were identified ("before 1980", "between 1981 and 2000" and "after 2001"), in line with the energy requirements in force in the respective periods [46]. Based on the distribution of SFHs and MFHs in the nine construction periods, the most populated periods were identified within the three macro-classes (see Figure 2.19). For each construction period, the most relevant RB within the TABULA database was selected as representative of that macro-class, leading to the identification of 6 RBs [46].

The 6 RBs from TABULA database were assumed in terms of geometry and efficiencies of the installed supply sub-systems, while they were further characterized in terms of thermal properties. Indeed, the Italian RBs identified within the TABULA project were mainly based on data from the Middle Climate zone E (2101 $<$ HDD $<$ 3000), and more specifically from Piedmont region [155]. In order to tackle the differences in terms of thermal properties of the buildings across Italy, TABULA original U-values were adjusted in accordance with Ref. [156]. For the different RBs, Italian average U-values were calculated, differentiating them according to building ages (see Table 2.11), and weighted on the frequency distribution of the main construction elements of SFHs and MFHs for each period across the whole country. Finally, the 6 RBs were further diversified considering the five geographical zones (i.e. North-West, North-East, Centre, South and Islands) reported in ISTAT classification [154].

Given the above, a total of 30 RBs was identified (6 RBs per each geographical zone). RBs were modelled using MasterClima software, setting thermo-physical



(a) SFHs (b) MFHs

Figure 2.19: Frequency distribution per construction periods: (a) single-family houses (SFHs); (b) multi-family houses (MFHs). Asterisks indicate the most relevant period of construction for each macro-class according to frequency distribution.

Table 2.11: Average Italian U-values of the main construction typologies of the RBs. Elaborated from [154, 156].

U-value $[W/m^2K]$			
Construction typology	**Before 1980**	**1981-2000**	**After 2001**
Floor	1.48	1.34	0.85
Ceiling	1.61	1.19	0.71
External vertical walls	1.28	1.05	0.73
External glazed surfaces	3.74	3.54	3.20

properties, internal temperature and ventilation requirements (all RBs are naturally ventilated), and energy needs for space heating were estimated by means of monthly quasi steady-state simulations, considering the climate conditions of Turin, Venice, Rome, Bari and Palermo as representative of the five geographical zones. Starting from the energy needs obtained through the simulations, and according to the generation efficiencies of the technologies to be compared (see Table 2.10), energy consumptions were computed, assuming the efficiencies of the other subsystems (distribution and emission) fixed (defined in accordance with TABULA [153]). Finally, for each RB, global costs and CO_2 emissions were computed for each technology, according to Eq. 2.25 and 2.26, in order to evaluate the expected evolutions of the competitiveness of the technologies in future years. Table 2.12 summarizes the assumed techno-economic parameters for the three technological options for the global cost assessment. Investment costs were derived from a review of main Italian price statistics; annual maintenance costs were assumed as percentage values of the initial investment costs, as defined by EN 15459 standard

[150]. A 5% interest rate was used for the global cost calculation.

Table 2.12: Assumed techno-economic parameters of the technological options for space heating system interventions.

Technology	**Typical lifetime** [*years*]	**Investment cost** [€/*kW*]	**Annual maintenance cost** [%]
Condensing gas boiler	20	100-137	1.5
Biomass boiler	20	460-570	2.0
Electric air-to-water heat pump	20	580-644	3.0

CO_2 emission factors were derived from Ref. [130], but, to be consistent with the choice of the timespan of analysis, electricity emission factors were varied, according to Ref. [157], assuming the probable evolution of the power generation mix. Moreover, Refs. [157, 158] were used to vary the prices of the energy commodities (i.e. natural gas, biomass, and electricity) in 2030 and 2050. In particular, specific literature-based growth rates were applied to 2015 (chosen as reference year in accordance with Ref. [46]) price statistics for gas, biomass and electricity. Both electricity and gas prices vary according to specific consumption bands. In this application, a particular attention was devoted to the electricity price, and its variations according to the existing tariff schemes. In 2015, a voluntary tariff experimentation for heat pumps was underway, aiming to render heat pumps more competitive on the market [159]. According to this experimentation, which was accessible only for buildings with autonomous systems and using heat pumps as the sole heating source, a non-progressive tariff for electricity (i.e. not dependent on actual consumption) could be voluntarily adopted. As shown in Table 2.13, the tariff convenience was strictly related to the annual electricity consumption of the buildings: the higher the consumptions (higher than 1800 kWh/year), the more convenient the tariff was. In order to take into account this possibility, for all the RBs characterized by autonomous heating systems (according to Ref. [153]), the model implemented for the global cost calculation automatically chooses the tariff experimentation only if the operational conditions render it more convenient than the normal price scheme.

Table 2.13: Variable fee values of the electric bill for 2015, before taxes application [159].

	Variable fee [€/*kWh*]
Annual consumption $<$ 1800 kWh/y	0.123
Annual consumption $<$ 1800 kWh/y	0.244
Heat pump experimental tariff	0.170

Given the above, a baseline scenario (BASE) was developed, which allowed the calculation of the financial and environmental KPIs for 2030 and 2050, to provide a snapshot of the future performances of the analysed technologies. According to the BASE scenario, GCES aggregate indicators were computed, after having identified, per each RB, the solution with the worst environmental but most financially performance.

It is clear that GCES indicators are strongly dependent on the boundary conditions used for the global cost assessment, which are in turn dependent on specific policies. For this reason, in order to estimate the impacts that different financial policies may have on the technologies performances and on their competitiveness, different instruments in terms of market regulation mechanisms (incentives and environmental costs) or pricing models (contract formulation variations) were investigated, to explore the global costs variations (and thus the GCES changes) caused by their introduction. Five alternative policy scenarios were built (as summarized in Table 2.14). In detail, two scenarios (INC and INCR) aimed to include existing incentive mechanisms into the global cost formulation. Specifically, two mechanisms were considered: Ecobonus (10 years-based tax rebate for buildings retrofit computed as percentages of the investment cost depending on the technologies [151]) and *Conto Termico 2.0* (financial contribute provided in 1, 2 or 5 annual rates for envelope or systems interventions on buildings [152]). In detail, the INCR policy scenario considered the adoption of either Ecobonus or *Conto Termico 2.0*, according to which is more advantageous for the different applications. All considered technologies can access Ecobonus, while condensing gas boiler is excluded from *Conto Termico 2.0*. Then, in line with an electrification perspective, to promote heat pumps with respect to more traditional technologies, INC scenario was developed assuming the adoption of incentive mechanisms (either Ecobonus or *Conto Termico 2.0* according to convenience) only for heat pumps. A specific scenario was built to investigate the electricity price formulation (TF scenario). A unique variable price for electricity (removing progressivity) was considered, assuming it equal to the lowest price for domestic consumers in each timespan (see Table 2.13). Differently from the tariff experimentation present in the BASE scenario, this tariff was assumed valid for all RBs, independently on the type of heating system. Finally, in order to translate buildings environmental impacts into financial burdens for the private investors, two scenarios were built assuming to introduce specific environmental taxes into the global cost calculation. Attention was devoted also to the local air pollution issue, which is considered as a major concern especially in urban areas, where the concentration of harmful local pollutants is alarming, especially in the winter season. It was estimated that almost 30% of PM emissions in EU are caused by heating systems [160], and fuel combustion for heating purposes is the main cause of air pollutant emissions, in the building sector. In line with the above, TXC and TXPM scenarios were developed, which considered the adoption of a taxation on the CO_2 (27.5 €/t for 2030 and 50 €/t for 2050 [161]) and PM

(0.087 €/g for 2030 and 2050 [161]) emissions, respectively, caused by space heating systems usage.

Table 2.14: Assumed policy scenarios.

Scenario	**Description**
INCR	Adoption of Ecobonus or *Conto Termico 2.0* according to convenience
INC	Adoption of Ecobonus or *Conto Termico 2.0* according to convenience only for heat pumps
TF	Adoption of a non-progressive electricity tariff for heat pumps
TXC	Taxation on CO_2 emissions generated by heating systems
TXPM	Taxation on PM10 emissions generated by heating systems

2.2.5 Key findings and discussion

This section summarizes the key findings resulting from the comparison of a set of existing technologies suitable for the retrofit of space heating systems in Italian residential buildings. These results, in line with the methodology developed within the thesis, aim to support policy makers, allowing to evaluate the future performances of the selected technologies and to formulate appropriate strategies for potentially encouraging their spreading, with a particular focus on the diffusion of electric solutions.

Based on the modelling of the technological alternatives for the 30 RBs, it was possible to draw the graphical decision support tool, providing to policy makers a snapshot of the financial and environmental performances of a set of space heating generation technologies, potentially applied in case of retrofit of different RBs. As mentioned before, even though the tool helps highlight the reciprocal positioning of different technologies within the x-y space, it is crucial to pay attention to the technologies potentially competing for the same RB. In this way, the decision-maker could drive conclusions on the likelihood of a technology to be preferred in case of retrofit and thus on the potential risk associated to its adoption, in environmental terms. Examples of the graphical tools are reported in Figure 2.20 and Figure 2.21 for 2030 and 2050, respectively, both focusing on the North-West geographical zone. Per each RB, three technologies were compared: condensing gas boiler, biomass boiler and electric heat pump. Each triplet is identified by the same filling and edge of the dots (the former is used to identify the construction period, while the latter to differentiate SFHs and MFHs; specifically, dots with no edge are used to represent SFHs, while the ones with solid edge correspond to MFHs). Finally, colour is used to indicate the technology (blue for gas, grey for biomass and green for heat pump).

In both 2030 and 2050, condensing gas boiler represents the solution with the worst environmental performance. Conversely, in financial terms, it appears that,

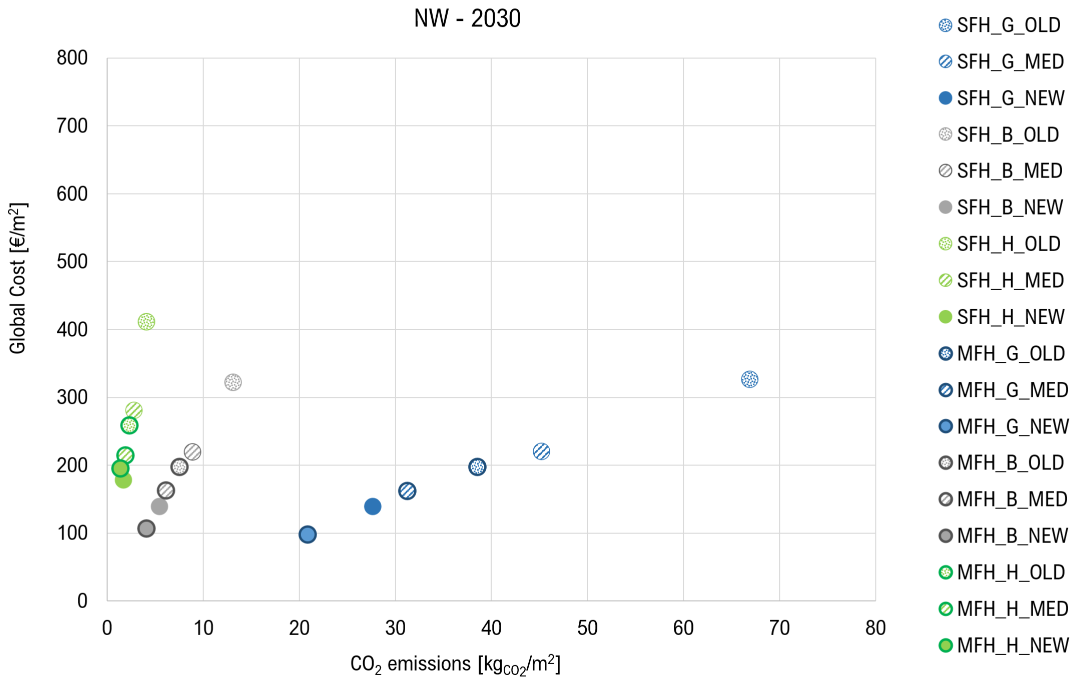


Figure 2.20: Graphical visualization of financial and environmental performances in 2030: focus on North-West. G = condensing gas boiler, B = biomass boiler, H = heat pump; OLD = before 1980, MED = between 1981 and 2000, NEW = after 2001.

in 2030, the solution with the lowest global cost does not always coincide with the most environmentally risky (i.e. condensing gas boiler), since for some RBs, biomass boiler appears to be the most attractive solution. Biomass and condensing gas boilers are highly competitive for the different RBs, while heat pump is always characterized by the highest global cost, due to its higher investment and operational costs. This situation does not occur in 2050, when, due to energy price projections, biomass boiler seems to be the solution with the highest global cost.

Based on this snapshot, GCES aggregate indicator was calculated only for the RBs where the solution with the worst environmental performance (i.e. condensing gas boiler) coincides with that with the lowest global cost. In 2030, in the North-West area, this situation occurs for all MFHs and for the SFHs built after 2001; in 2050, for the same geographical zone, this situation occurs in all RBs. In theses cases, the GCES was calculated according to Eq. 2.27 with respect to the environmentally worst solution. The calculation of the aggregate indicator aims to evaluate how much the other better environmental-friendly solutions cost in relation to the benefits that their adoption could guarantee in terms of CO_2 emissions

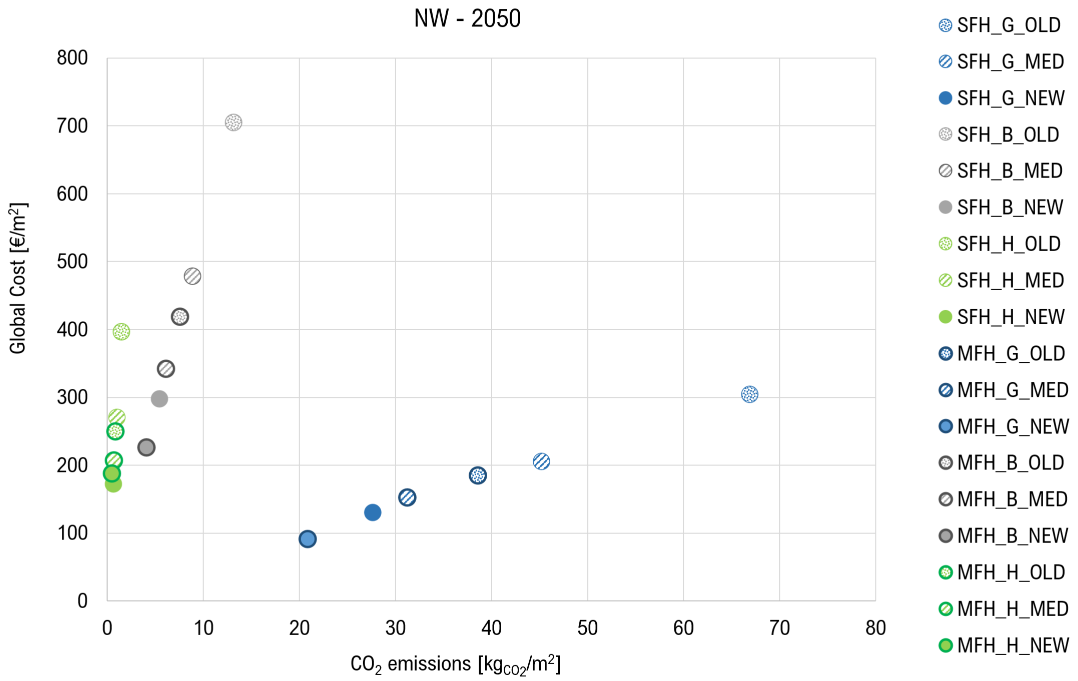


Figure 2.21: Graphical visualization of financial and environmental performances in 2050: focus on North-West. G = condensing gas boiler, B = biomass boiler, H = heat pump; OLD = before 1980, MED = between 1981 and 2000, NEW = after 2001.

savings, in case they are preferred to the condensing gas boiler, which nowadays is the most widely deployed technology in the residential sector [36, 151]. The graphs of Figure 2.20 and Figure 2.21 refer to the BASE scenario (reflecting the original boundary conditions), and its associated GCES indicators are summarized in Table 2.15 and Table 2.16, together with those of the other geographical zones (blank cells represent the RBs for which the GCES is not computed). As shown, the results are strongly dependent on the geographical area, which can affect the operational conditions of the alternative solutions. For instance, in North-East, South and Islands, GCES is calculated for all RBs, while in the Center it happens only for SFHs and MFHs built after 2001. By definition, for each RB, among the two options, the best trade-off is represented by the solution with the lowest GCES indicator. From Table 2.15 and Table 2.16, it emerges that, in 2030, biomass boiler presents the lowest aggregate indicator for all the RBs in which GCES is computed, while an opposite result is achieved in 2050, when the electric heat pump reaches the lowest indicators for all the studied RBs.

Table 2.15: GCES values for SFHs and MFHs for 2030 [€/kg_{CO_2}]. NW = North-West, NE = North-East, CE = Centre, SO = South, IS = Islands.

SFHs						
Construction period	**Technology**	**NW**	**NE**	**CE**	**SO**	**IS**
Before 1980	Biomass boiler		5.98		6.93	7.36
	Electric heat pump		6.57		7.59	8.19
1981 - 2000	Biomass boiler		6.08		7.14	7.70
	Electric heat pump		6.63		7.83	8.47
After 2001	Biomass boiler	6.25	6.33	7.39	7.66	8.43
	Electric heat pump	6.86	6.98	8.26	8.56	8.59
MFHs						
Construction period	**Technology**	**NW**	**NE**	**CE**	**SO**	**IS**
Before 1980	Biomass boiler	6.36	6.43		7.83	8.61
	Electric heat pump	7.12	7.25		7.98	9.34
1981 - 2000	Biomass boiler	6.46	6.51		8.06	9.19
	Electric heat pump	7.28	7.40		8.36	10.29
After 2001	Biomass boiler	6.31	6.39	7.63	8.09	11.02
	Electric heat pump	9.97	10.12	11.88	12.55	13.53

Table 2.16: GCES values for SFHs and MFHs for 2050 [€/kg_{CO_2}]. NW = North-West, NE = North-East, CE = Centre, SO = South, IS = Islands.

SFHs						
Construction period	**Technology**	**NW**	**NE**	**CE**	**SO**	**IS**
Before 1980	Biomass boiler	13.12	13.11	13.62	14.06	14.49
	Electric heat pump	6.06	6.08	6.60	7.06	7.63
1981 - 2000	Biomass boiler	13.17	13.21	13.98	14.27	14.83
	Electric heat pump	6.11	6.14	6.99	7.29	7.90
After 2001	Biomass boiler	13.38	13.45	14.51	14.79	15.56
	Electric heat pump	6.36	6.47	7.70	7.99	8.08
MFHs						
Construction period	**Technology**	**NW**	**NE**	**CE**	**SO**	**IS**
Before 1980	Biomass boiler	13.48	13.56	14.55	14.96	15.73
	Electric heat pump	6.60	6.74	7.02	7.49	8.80
1981 - 2000	Biomass boiler	13.58	13.64	14.67	15.18	16.32
	Electric heat pump	6.76	6.88	7.25	7.86	9.70
After 2001	Biomass boiler	13.46	13.54	14.78	15.24	18.15
	Electric heat pump	9.20	9.34	11.03	11.66	12.67

By definition, the GCES indicator is dependent on the global costs of the selected technologies, in turn influenced by the fixed boundary conditions for their calculation. Therefore, the interest of a policy maker aiming to push the market in a certain direction should be that of investigating to what extent variations of the original boundary conditions might influence the competitiveness between the alternative technologies (in terms of GCES indicators). In particular, the policy maker should aim to minimize the GCES, by lowering the numerator (global cost), being the denominator fixed by buildings operations and systems efficiencies. Figure 2.22 and Figure 2.23 show the effects of the policy scenarios in terms of GCES percentage variations with respect to BASE scenario, for the cases in which GCES can be computed in BASE, for 2030 and North-West area. In case the policy measure induces a lowering of the GCES, thanks to a decrement of the original global cost, a negative result is visible.

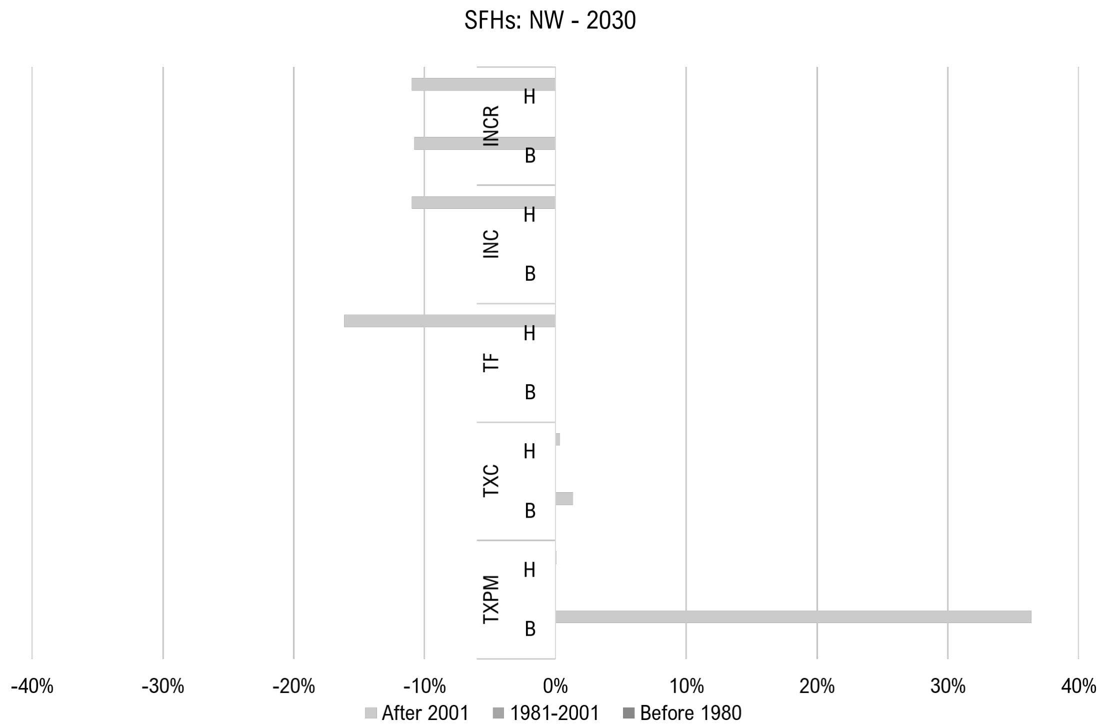


Figure 2.22: GCES percentage variations with respect to the BASE scenario in 2030: focus on SFHs in North-West. B = biomass boiler, H = heat pump.

Only TXC and TXPM scenarios induce positive GCES variations (meaning that GCES has increased with respect to the BASE scenario); these scenarios, indeed, foresee an increment of the global cost of all technologies, due to the introduction of appropriate environmental taxes on the generated emissions (CO_2 and PM, respectively). As shown in Figure 2.22 and Figure 2.23, TXC barely affect the biomass/heat pump competition, since both technologies generate low amounts of CO_2 emissions (due to the assumed green evolution of the electricity generation mix). However, a different situation is visible when considering the TXPM scenario,

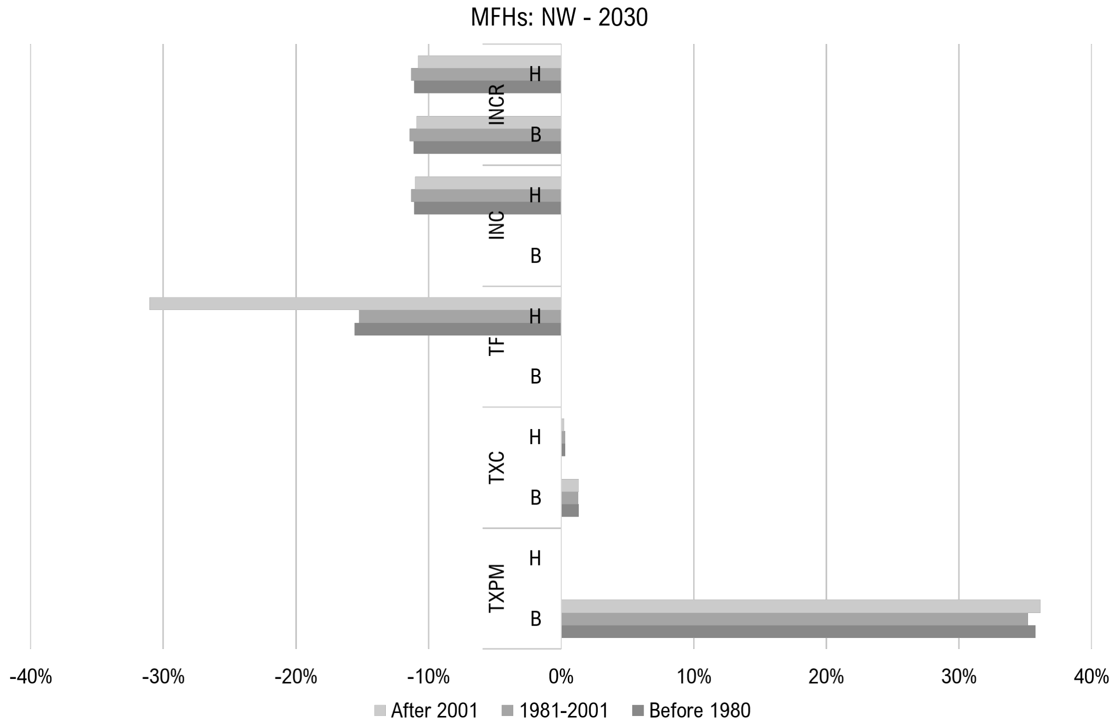


Figure 2.23: GCES percentage variations with respect to the BASE scenario in 2030: focus on MFHs in North-West. B = biomass boiler, H = heat pump.

for which it is possible to notice a greater percentage variation for the biomass boiler, being it the largest PM emitter among the alternatives.

TF scenario only affects heat pump indicators, since this scenario focuses on electricity prices, by evaluating the adoption of a non-progressive tariff not dependent on the annual electricity consumption. Surely, the effect of this policy scenario on the GCES depends on the specific RBs and on the geographical areas. In MFHs, the greatest variations are experienced for the RB built after 2001, which deserves a separate discussion. Indeed, among the RBs selected from TABULA, this RB is the sole with a centralized heating system, and thus the only one excluded from the 2015 tariff experimentation for the heat pumps. Due to the high electricity consumptions, in the BASE scenario, the highest electricity tariff was charged to this RB. For this reason, as shown in Figure 2.23, TF scenario presents the highest negative GCES percentage variations for this RB, meaning that this policy scenario is capable of inducing a huge decrease of the heat pump global cost.

Finally, both INC and INCR scenarios consider the addition of the incentive mechanisms into the global cost formulation. If the INCR assumes to adopt the most convenient incentive mechanism (among *Conto Termico 2.0* and Ecobonus) for all the technologies that can access them, the INC scenario considers the incentive adoption only for the electric heat pump, to evaluate specific policies aiming to further boost the electrification of the heating service. Therefore, the effect of the INC scenario can only be a reduction of the global cost of the heat pump solution, thus producing a negative percentage GCES variation for this solution, without affecting the GCES of the biomass boiler. For the electric solution, it is clear that INC and INCR scenarios induce equal variations, since both scenarios consider the adoption of the most convenient incentive mechanism.

In this regard, in order to compare the effect of the two incentive mechanisms considered, namely Ecobonus and *Conto Termico 2.0*, two additional scenarios were built, in which both instruments were separately applied to the three technologies (see Figure 2.24 and Figure 2.25). Specifically, ECO scenario considers the adop-

Figure 2.24: Effects of incentive mechanisms on the GCES percentage variations with respect to the BASE scenario in 2030: focus on SFHs in North-West. B = biomass boiler, H = heat pump.

tion of the Ecobonus mechanism for all considered technologies, and CT evaluates the access of only biomass boiler and electric heat pump to *Conto Termico 2.0*, being condensing gas boiler already excluded by the mechanism. From Figure 2.24 and Figure 2.25, it is evident that the highest variation of GCES indicator with respect to BASE scenario is induced by Ecobonus, for both SFHs and MFHs, being at least twice the variation of the CT scenario. According to the results, it is

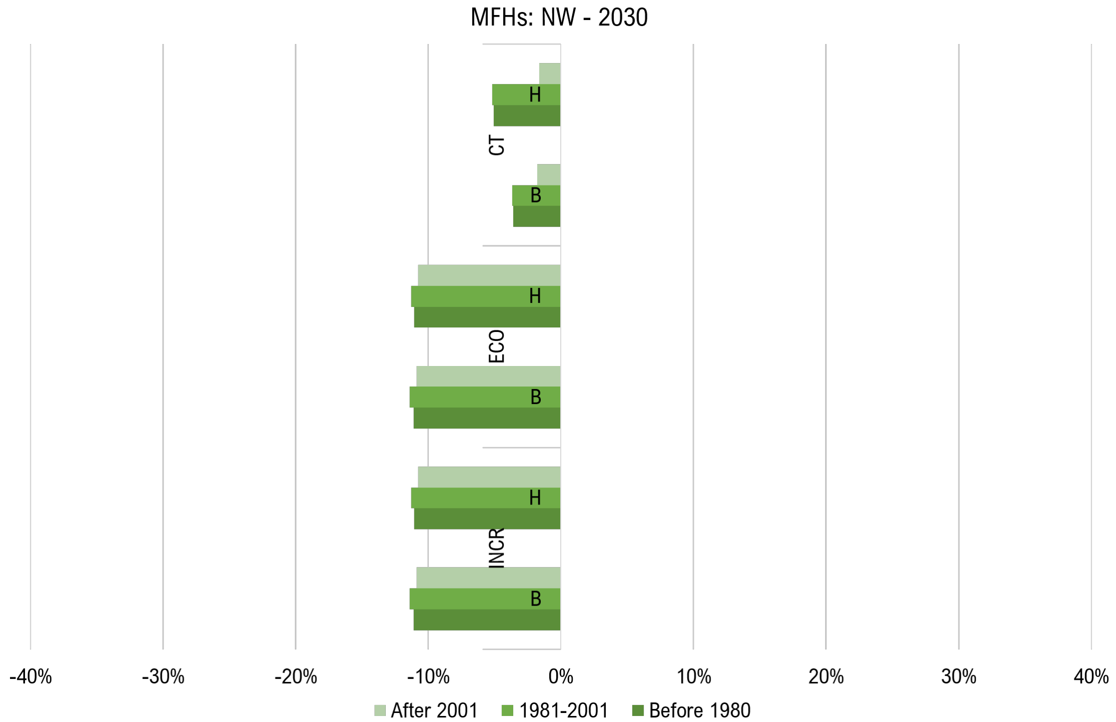


Figure 2.25: Effects of incentive mechanisms on the GCES percentage variations with respect to the BASE scenario in 2030: focus on MFHs in North-West. B = biomass boiler, H = heat pump.

possible to note how the INCR scenario, which assumes to access the most convenient incentive mechanism for all technologies, considers the adoption of Ecobonus for both biomass boiler and electric heat pump. Finally, exploring the reciprocal behaviour of the two competing solutions, it is possible to note that ECO scenario leads to similar percentage values for biomass boilers and heat pumps, while the CT slightly advantages the heat pump over the biomass boiler.

The same considerations were drawn for 2050, which main results are shown in Figure 2.26 and Figure 2.27 for the North-West area. Conversely to 2030, in 2050, GCES indicators were computed for all RBs, since the condensing gas boiler always appeared to be the best choice in financial terms (see Table 2.16) and this condition is not affected by the policy scenarios. Therefore, the graphs of Figure 2.26 and Figure 2.27 are more populated than in 2030. However, the considerations drawn for 2030 are still valid for 2050. INCR scenario is the sole able to induce a negative variation to the GCES indicator of the biomass boiler, thanks to the introduction of the incentive mechanisms also for this technology. Conversely, the other scenarios affecting biomass boiler indicators are TXC and TXPM, which induce positive GCES variations. Finally, as commented above, INC and TF affects only the heat pump technology, with the highest impact caused by the tariff variation, for both SFHs and MFHs, meaning that this scenario is the one most probably able to make the electric solution more competitive on the market.

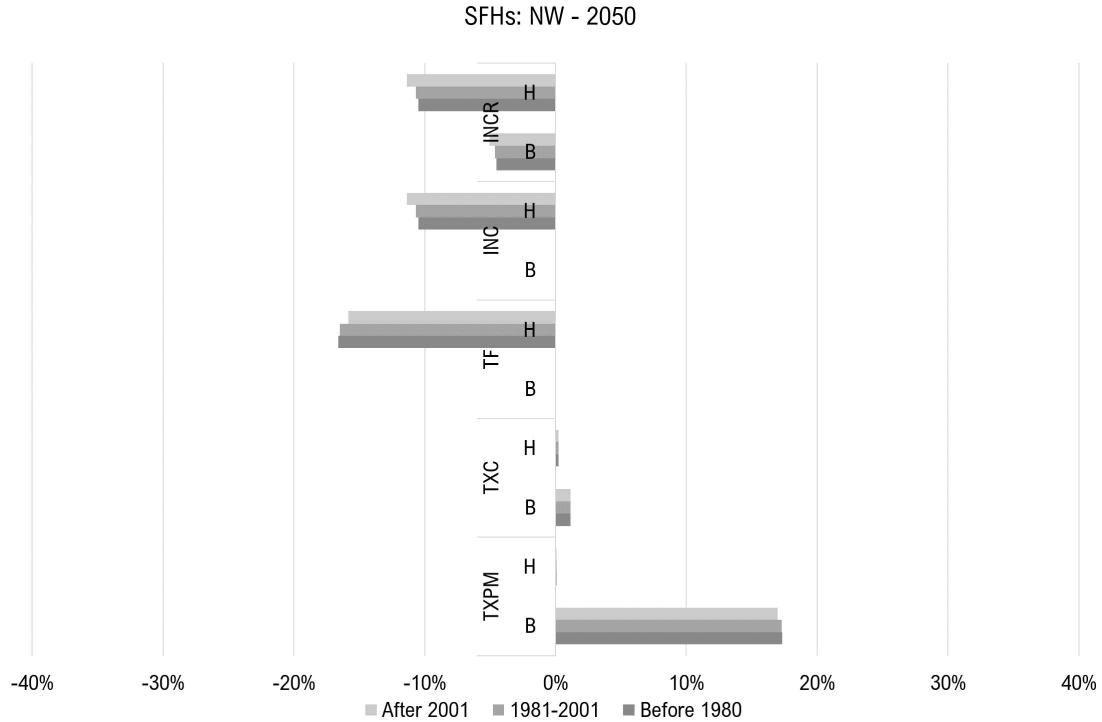


Figure 2.26: GCES percentage variations with respect to the BASE scenario in 2050: focus on SFHs in North-West. B = biomass boiler, H = heat pump.

What has been said so far helped to highlight the effects that each policy scenario separately has on the single solutions. However, in order to explore the possible future spreading of electric solutions to foster the transition of the building sector, it is interesting to explore how the alternative scenarios may influence the relative competitiveness between biomass boiler and electric heat pump. In particular, attention was devoted to highlight which policy measure might guarantee a switch of competitiveness, in favour of electric technologies. In detail, the relative competition is provided in terms of $\Delta GCES$ between the two solutions, as reported in Eq. 2.30:

$$\Delta GCES = GCES_B - GCES_H \tag{2.30}$$

where $GCES_B$ and $GCES_H$ represents the GCES indicators for biomass boiler and electric heat pump, respectively. A positive $\Delta GCES$ means that the choice of the electric solution over the biomass boiler can provide an advantage for the private investor ($GCES_B$ greater than $GCES_H$), while a negative value of the $\Delta GCES$

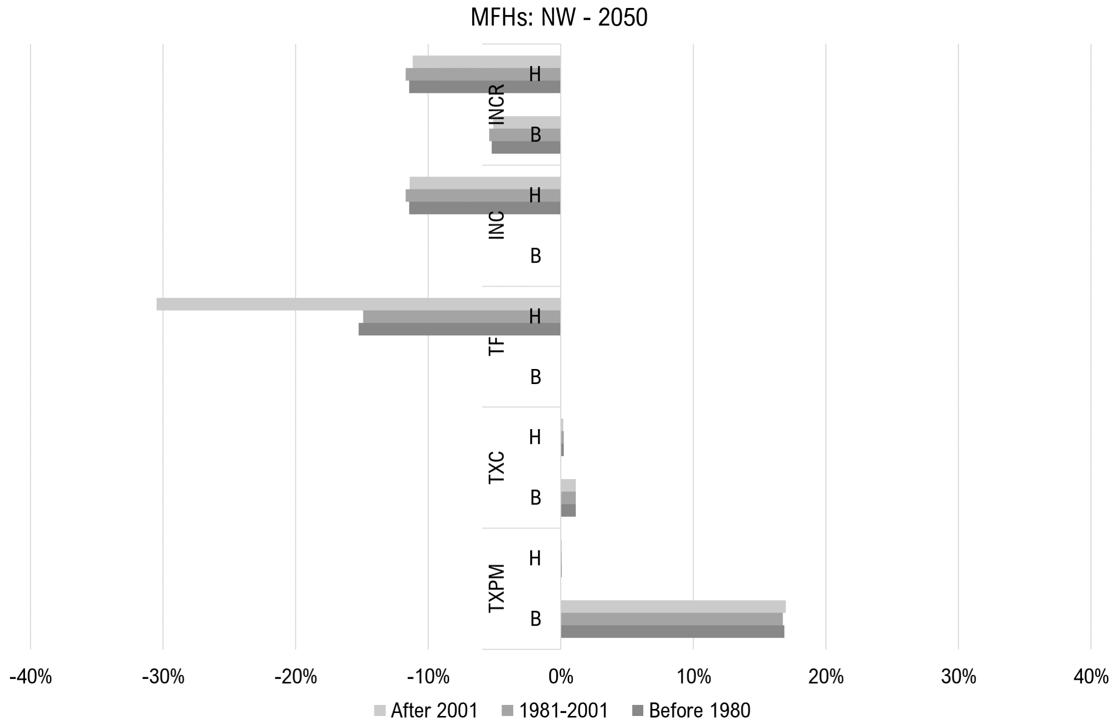


Figure 2.27: GCES percentage variations with respect to the BASE scenario in 2050: focus on MFHs in North-West. B = biomass boiler, H = heat pump.

corresponds to a greater benefit coming from the adoption of the biomass boiler. Thanks to this calculation, the policy maker is able to easily understand the effects of a specific measure on the competition between the two technologies, and thus to highlight how its implementation would push the market towards one or another alternative. As exemplification of results, $\Delta GCES$ for the SFHs and MFHs built before 1980 in 2030 are reported in Figure 2.28 and Figure 2.29.

In accordance with the GCES outcomes reported in Table 2.15, in the BASE scenario, the biomass boiler always appears to be more competitive than the electric heat pump; for this reason, the BASE scenario is always characterized by negative $\Delta GCES$ values. Coming to the scenario analysis, INCR scenario (yellow bars) is not able to change the competitiveness, since this scenario assumes the possibility of accessing the incentive mechanisms for both technologies, thus favouring them in equal terms. A similar result is achieved with the TXC scenario (light blue bars), which presents almost null variation with respect to the BASE case, since both technologies cause low CO_2 emissions, and thus this taxation has a small impact on the GCES values. Conversely, the TXPM scenario (green bars), even though it does not result in a GCES lowering for the two technologies, greatly affects their relative competitiveness, due to the high environmental impact caused

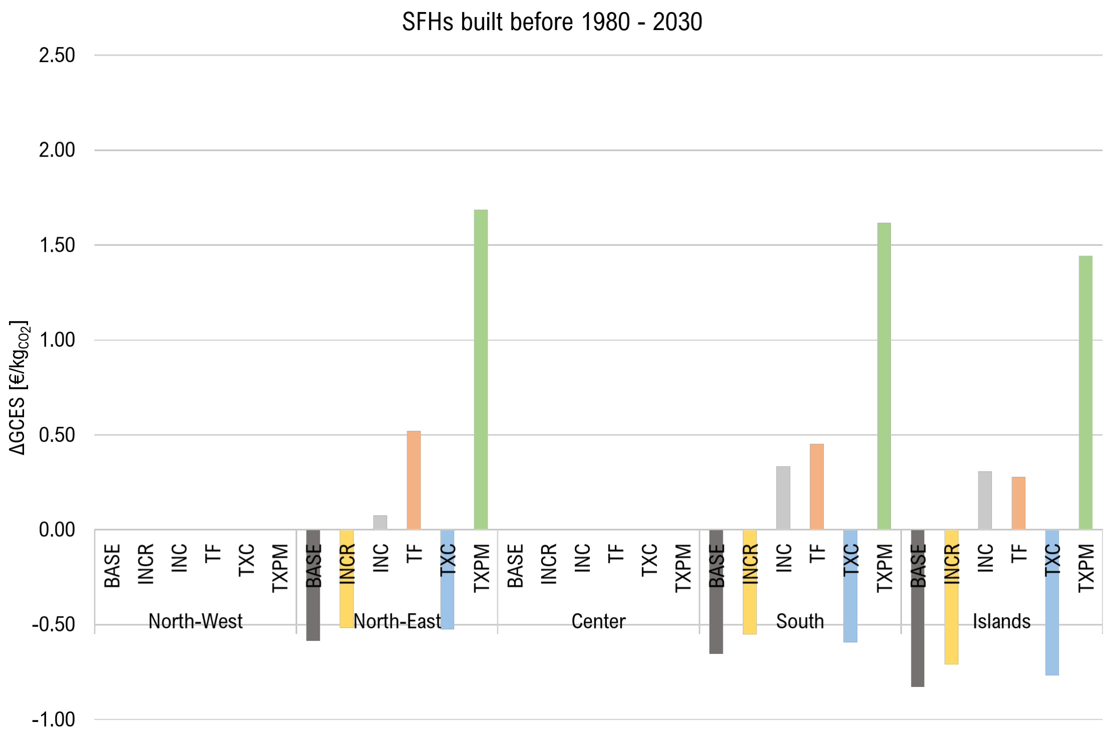


Figure 2.28: $\Delta GCES$ for different scenarios in 2030: focus on SFHs built before 1980.

by the biomass boiler in terms of PM emissions (80:1 ratio between biomass and electricity PM emission factors [160, 162]). As shown in Figure 2.28 and Figure 2.29, for both SFHs and MFHs, in all geographical zones the TXPM scenario allows a change of competitiveness in the technological ranking, since the $\Delta GCES$ becomes positive with respect to the BASE scenario. This scenario is the one provoking the greatest delta between the two technologies, highlighting how the introduction of appropriate environmental taxes could favour better performing technologies; moreover, due to the differences between TXC and TXPM, it is fundamental for policy makers to introduce ad-hoc policies tackling the local air quality issue.

Finally, INC and TF scenarios deal with measures that only affect the heat pump option, thus favouring the competition towards electrification. Even though these scenarios are both able to change the competitiveness in favour of heat pumps for almost all RBs, their relative effect is dependent on the operational conditions. Specifically, the effect of the TF scenario is stronger for RBs with high energy consumptions, for which the energy cost is the strongest voice in the global cost calculation; on the other hand, for the RBs with low energy consumptions, the incidence of the energy cost on the overall global cost assessment decreases, making other cost voices (i.e. incentive mechanisms) gaining weight. In SFHs (see

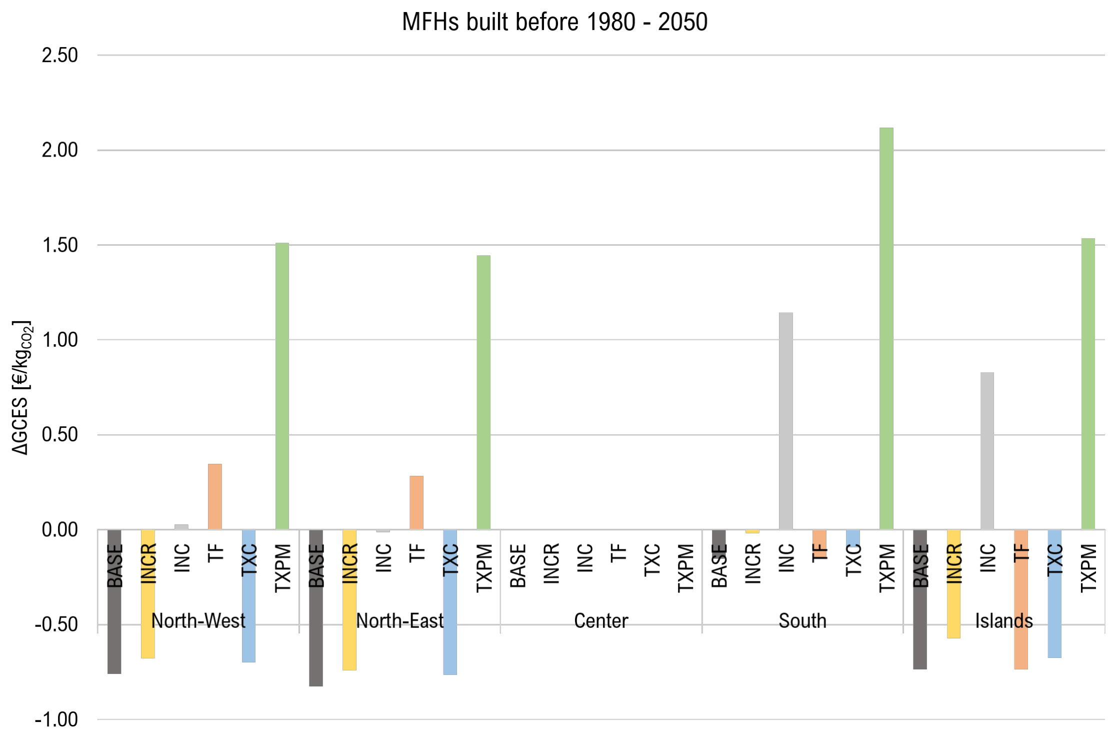


Figure 2.29: $\Delta GCES$ for different scenarios in 2030: focus on MFHs built before 1980.

Figure 2.28), this situation is visible for the Islands, where RBs present low annual consumptions; in these conditions, INC scenario leads to a greater $\Delta GCES$ difference than TF. The same condition is visible for MFHs in South and Islands regions, as reported in Figure 2.29. It is interesting to note that, in these cases, the adoption of the non-progressive tariff does not have any effect on the $\Delta GCES$ and on the priority change between biomass boiler and heat pump, since the new tariff envisaged by the TF scenario is identical to the price scheme already adopted by these RBs in the BASE scenario. On the other hand, for the RBs with high energy consumptions, the weight of the energy cost is higher; therefore, the greatest impacts with respect to the BASE scenario are achieved when considering policy measures affecting (reducing) the cost of electricity (i.e. TF scenario). Besides the trend and the relative effect between INC and TF scenarios, both are able to change the priority between biomass boiler and heat pump with respect to BASE (from negative to positive $\Delta GCES$ values), with the only exception of the MFHs located in South and Islands regions.

2.2.6 Conclusions and further investigation

The impact of the building sector on society and environment is well known and strong efforts are still needed to meet the ambitious targets defined for it. In order to monitor and evaluate the strategies in place to boost the energy efficiency improvement of individual buildings and, mainly, of HVAC systems, the use of KPIs has become common. If well-defined, KPIs allow to monitor and set medium- and long-term objectives, as well as to translate measured data into usable knowledge. Moreover, since the transition of the building sector is not only energy-related, the definition and use of ad-hoc multi-dimensional metrics allows to effectively combine different perspectives, which are often contrasting among them, in order to capture all the benefits arising from energy efficiency interventions.

In line with the above, the work presented in this section aimed to support the decision-making process for the energy planning of buildings, by defining appropriate KPIs able to assess the performances of building technologies from a multi-dimensional point of view. In particular, ad-hoc decision-making support tools, both graphical and analytical, were defined, with the aim of providing a forecast of the effects of a baseline and of alternative policy scenarios on the reciprocal convenience of different technologies (i.e. thermal generators for space heating). The drawing of the graphical decision-support tool, as well as the definition of the GCES aggregate indicator permitted to stress the importance of integrating different perspectives into the evaluation of the convenience of a retrofit option. Indeed, thanks to the application to the Italian case, it was possible to verify how private (financial) and public (environmental) objectives can be often contrasting among them. Specifically, the definition of the GCES indicator allowed to identify the solutions representing better trade-offs between these perspectives. Moreover, the work permitted to identify the key role that policy makers will play in driving consumers' choices towards the adoption of low-carbon technologies. In particular, through the use of the aggregate GCES indicator, the definition of alternative policy scenarios allowed to estimate the effect of existing or innovative policy schemes on the reciprocal convenience of the technologies under investigation. Indeed, in line with the public goal of reducing the environmental impact of the sector, the application allowed to discuss on the instruments at disposal to translate the environmental burdens of some solutions into financial terms, in order to potentially boost the diffusion of more environmental-friendly options.

The analysis encourages further work, which can be devoted to develop new indicators, reflecting also the perspectives of other stakeholders potentially involved in the renovation process and not tackled in this application (e.g. manufacturers, service providers, designers, etc.). Due to the actual concern on local pollution, a different perspective can be obtained by using the PM emissions generated by the different retrofit options in place of the considered CO_2 emissions, which can potentially result in diverse outcomes and considerations.

The work was limited to the sole thermal generator substitution, using a simplified technological assessment, without considering the potential coupling of the analysed generation technologies with different emission sub-systems (e.g. radiators, radiant systems, etc.) with diverse temperature levels. For future development, aiming to overcome the encountered limitations, different technological solutions could be analysed, as well as the coupling of technological intervention with envelope retrofit, which was not accounted in this application. In particular, due to the modest U-values considered for the simulated RBs, the effect of envelope insulation on the reciprocal positioning of the technological solutions in the graphical decision-making tool and on the forecast of the technological competitiveness would be worth to explore. A preliminary extreme scenario was developed analysing the coupling of the complete renovation of opaque and transparent envelope (according to regulatory requirements for the different climate zones in Italy) with the studied substitution of the thermal generators. This scenario results in a higher closeness of the points in the graphical tool in terms of environmental performance; however, the competitiveness between the technological solutions would not be greatly altered, being all options associated to the same heating needs reduction. Further investigation on this issue will be worth to discuss, also considering diverse envelope retrofit scenarios, coupled with system intervention or renewable sources integration.

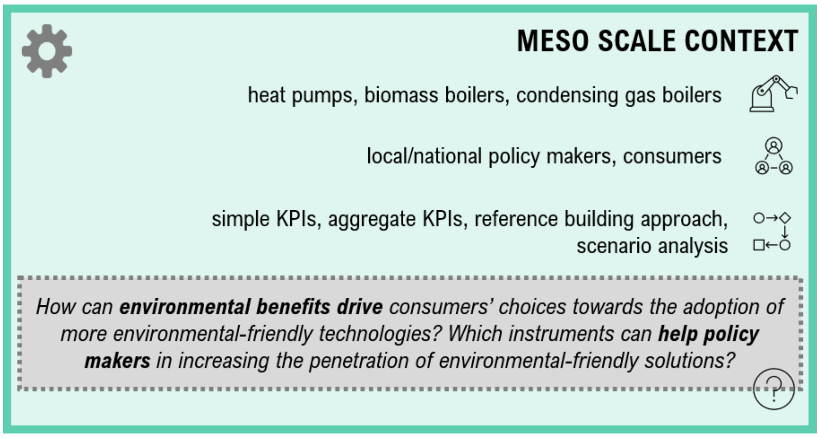
Moreover, future work could be devoted to the analysis of other end-uses, as domestic hot water and space cooling. The latter service is interesting to analyse due to increasing demand for air conditioning, especially in the Mediterranean region. In this regard, it is important to cite that the use of a reversible heat pump would guarantee a double service (heating and cooling) at once, against a single investment; conversely, a biomass or a condensing gas boiler would request the installation of a separate space cooling technology, requiring an additional investment cost. The assessment and definition of an opportunity cost that permits to compare the services that the solutions can provide in equal terms could represent a further momentum to the penetration of electric technologies in the building sector.

Despite the present limitations, the application to the case study represents an exemplification of the developed methodological framework, which can be replicable in different contexts and further deepened. The methodology could be used also for non-residential buildings, even though some difficulties might arise from the scarcity of RBs for these building categories, as well as the difficulty in categorizing and classifying the non-residential stock, due to its peculiar and scattered characteristics.

Besides the application at building scale, this work could be used as the basis for the development of future scenarios of technological penetration at regional or national scales, using indicators of likelihood of technology diffusion, as the GCES, as forecasting tools for future technological-oriented uptake scenarios. To this purpose, a scale shift is requested, moving the lens from the individual buildings scale to the entire stock; this topic will be addressed in the following chapter, which will be devoted to the analysis of the electrification potential of the building sector at a meso scale, using an appropriately defined multi-dimensional aggregate indicator to reflect the private technological choices in case of retrofit of the thermal generators.

Chapter 3

Meso scale context



Starting from the previous considerations and shifting from a micro to a meso perspective, this chapter focuses on the national scale, aiming to simulate a scenario awarding the diffusion of more environmental-friendly solutions for satisfying the residential thermal uses, developing medium- and long-term scenario analyses, run in order to forecast the spreading of electricity-based technologies in the building sector. The chapter is focused on the development and use of simple and aggregate multi-dimensional KPIs as tools for forecasting consumers' choices, in case of retrofit of the thermal generators, imaging an hypothetical scenario in which environmental benefits can drive consumers towards the adoption of more environmental-friendly solutions. Moreover, in line with the attention on the benefits associated to a wider electrification of final uses, the chapter aims to estimate the contribution of electrification to the overall reductions of energy consumptions and emissions forecasted by the developed scenario analyses.

3.1 Indicators to value technologies for forecast-oriented purposes

3.1.1 Overview

Appropriate national long-term strategies for the building sector are needed with the scope of accelerating the renovation of the existing building stock. To this purpose, suitable building stock models are needed to help decision-makers to identify possible roadmaps for the improvement of the national building stock, as well as to test and explore the effects of specific policy strategies on the sector evolution. In line with this, this section studies the building sector from a national perspective, aiming to analyse possible pathways of decarbonization and electrification of residential buildings on a medium- and long-term horizon, focusing on thermal uses. Starting from the considerations reported in the previous section, attention is shifted from the single building level to a wider territorial scale, taking advantage of the reference building approach in support of the national stock modelling. The technological-oriented forecasting study is based on the development and use of appropriate KPIs able to compare and rank the technological options at disposal in case of retrofit from a multi-dimensional perspective. In particular, the analysis extends the work proposed in section 2.2, by developing a new aggregate KPI able to value environmental-friendly technologies and to transfer their environmental benefits into financial terms. Differently from the previous application, which used the developed GCES indicator for policy-oriented purposes, the newly-defined aggregate indicator is here deployed for forecast-oriented scopes. Specifically, the indicator is used as a forecasting instrument, to reflect consumers' choices in case of retrofit of the generation system, analysing an hypothetical condition in which investors' or consumers' retrofit decisions are not driven only by financial attractiveness and convenience, but are also influenced by the environmental benefits that the alternative generation technologies can guarantee with respect to the original conditions of their households systems. The medium- and long-term scenario analysis allows to design a possible roadmap of energy efficiency improvement and electrification of the Italian residential stock.

Keywords Residential building sector, medium- and long-term scenario analysis, Key Performance Indicators, electrification, thermal uses, national scale pathway, reference building approach.

Declaration Part of the topics described in this chapter were previously published in the following publications:

- E. Bompard et al., *Electrify Italy*, Fondazione Centro Studi Enel, 2020 [46].

- **G. Crespi**, E. Bompard, *Drivers of energy transition of Italian residential sector*, REHVA Journal 57, pp. 6-10, 2020 [131].

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3.1.2 Background

Energy efficiency improvement for the building sector represents a priority for decarbonization [144], together with its electrification. Focusing on heating and cooling sectors, a wider electrification of final uses can bring several benefits, among which the reduction of carbon intensity and GHG emissions (when coupled with a renewable electricity generation mix), the reduction of local air pollution and, thus, the improvement of air quality and mitigation of health effects on people [59]. Due to the potential impacts that the spreading of electric technologies at end-use level can have on the power sector, as stated by Thomaßen et al., the analysis of potential electrification pathways for the building sector is fundamental, to lately accompany and foresee future investments also in other sectors [59]. Despite the benefits that electric technologies can bring [47, 59, 60, 61, 65, 66], their penetration in the building stock still faces some barriers, mainly economic. Indeed, as highlighted in section 2.2, in the case of building retrofit, economics is still the main motivator driving investments, while "environmental and climate-based consequences are not seen to be part of the decision-making process" for individuals [56]. For this reason, as discussed, the role of policy makers is fundamental to set adequate measures and policies for effectively driving the sector transition.

An effective policy design, able to push the market towards the adoption of low-carbon technologies, needs to be supported by appropriately "robust and accurate models" [144]. As stated by Zhou et al., when evaluating possible policy strategies for energy and carbon savings achievements, *ex-ante* evaluations are part of the energy planning process [163]. In particular, the role of building stock modelling for policy and decision-making support purposes has been greatly discussed in literature [142, 144, 163], and, particularly, building stock models are recognized as relevant tools for estimating the impacts of the implementation of specific policy measures, aiming to assess the current conditions of the local/regional/national building stock, as well as to explore and monitor the potential future effects deriving from the introduction of specific policy strategies over time [103, 142, 144]. Still, according to Zhou et al., "modelling plays a key role in the evaluation process by allowing for the investigation of the trajectories of energy and emissions and enabling experimentation with potential policy interventions, therefore exploring possible pathways towards transformation to a highly energy efficient and low-carbon buildings and construction sector" [163]. As stated by Ballarini et al., medium-and long-term scenario analyses are needed to estimate the evolution of the energy demand of the building sector, in order to investigate the actions able to influence and drive its transformation [148]. In particular, long-term scenarios must be supported by models and tools able to evaluate the development and implementation of different energy efficiency actions on buildings [164], starting from the knowledge of the energy-related characteristics of the building stock components [165]. In this regard, and in line with the discussions reported in section 2.2, bottom-up engineering modelling techniques are identified as promising "policy and strategy development tools" [142]. Indeed, the archetype approach allows not only to evaluate the current state of a given building stock, but also to perform energy-related scenario analyses [166] and to model the performance of large building portfolios, supporting regional- or national-based policies [165]. For these reasons, they are widely used as "part of an evidence-based approach to medium- to long-term energy supply strategy" [144].

In line with the previous application, the analysis concentrates on the residential sector, which represents the largest portion of the EU building sector [48]. In this regard, many authors have recognized the need to identify appropriate national-scale renovation strategies and policies for residential buildings, in order to minimize its impact and boost its transformation [165]. To accomplish this, a scale shift is needed. If, in the previous section, attention was mainly devoted to the modelling of the operational contexts in which specific technologies can be potentially installed (i.e. individual representative buildings) to assess their performances from a multiple perspective, this section concentrates on the use of building models for the analysis of the whole national building stock; therefore, the role of electricity is still assessed at end-use level, but shifting from a micro scale (technological/individual building) perspective to a meso scale (entire national stock) standpoint, of interest for the definition of long-term strategies for the transition of the building sector. As reported in Besagni et al., "understanding the "country-scale" implication relies on a detailed description of the "household-scale"" [167] and this consideration is fully in line with the deployed RB concept (already described in section 2.2), which allows to study the effect of the spreading of particular technologies on the performances of the modelled representative buildings, which can be then extrapolated for broader "territorial scales" (e.g. city, region, nation, etc.) [144]. Furthermore, the analysis stresses the different interests of the private and public stakeholders involved in the process of retrofit interventions, already pinpointed in the previous section. Indeed, as well reported in Ang et al.'s work, on the one side policy makers are interested in developing strategies at stock level, in order to find the right measures able to reduce the environmental impact of the sector; on the other side, building owners/investors are more interested in understanding the savings associated with a particular technology or retrofit measure, with an individual building perspective [145].

This chapter presents a technological-oriented study, aiming to identify the medium- and long-term electrification potential for the Italian residential building stock, as well as to estimate the contribution of an electrification pathway to the overall reduction of energy consumptions and emissions. Indeed, as reported by Swan et al., according to the decarbonization objectives for the building sector, there is the need to study the spreading of alternative and low-carbon technologies and sources against more traditional ones [142]. In line with this, in the present application, retrofit scenarios at stock level are built aiming to reduce the carbon emissions from the sector, thus prioritizing retrofit interventions for the most impacting reference buildings within the stock. Even though current renovation rates do not allow to intervene on the totality of the building stock [168], in this way it is possible to identify the buildings that "represent a top priority for GHG abatement" [168]. Moreover, technological shifts are identified based on a multi-perspective aggregate indicator, aiming to synthesize the private and public perspectives. Indeed, the procedure used for the technology selection when a retrofit occurs (i.e. substitution of the generator for thermal uses) is based on the definition and use of an new KPI able to hypothetically drive the choices in case of retrofit of existing buildings. In this sense, the analysis here reported extends the work proposed in section 2.2, by developing a new combined KPI able to transfer the environmental benefits of building technologies into financial terms, but with a different scope and form. In detail, the previous GCES was defined specifically to assess the competitiveness of diverse technological solutions from the policy maker standpoint, in order to help her/him identifying the possible risks associated to financially-driven individual choices and, thus, defining appropriate policy measures or strategies able to drive consumers' choices. In this section, instead, the newly-developed indicator is used as a forecasting instrument, able to drive and reflect consumers' choices in case of retrofit, in case they are based on the environmental benefits that the compared solutions can bring, with respect to the environmental performances of their building in the current state. In line with this, the defined multi-layered methodological approach is applied to study possible technological trends and to investigate the electrification potential for the residential building sector. Focusing on the Italian residential sector, the application aims to provide a building stock modelling framework able to express the potentiality of the future spreading of electricity-fuelled technologies in the Italian panorama, developing an hypothetical scenario in which retrofit choices are not exclusively driven by economic motivations, and analysing how effective policy strategies can further boost and enable an electrification pathway.

3.1.3 Methodology

This study aims to assess the potential for further electrification of the residential sector, focusing on thermal uses (space heating and domestic hot water); the analysis of future possible technological uptake trends in the thermal uses was performed through the comparative assessment of competing technological options to be potentially installed when a system retrofit occurs. To this purpose, a two-phases methodology was adopted, as exemplified in Figure 3.1:

- **preparation phase: building stock baseline definition**. The baseline residential stock is properly quantified, characterized through the RB approach and adjusted in accordance with available statistics.
- **development phase: scenario analysis for thermal uses**. A possible future mid- and long-term scenario (2030 and 2050) of technological spreading is assessed, defining priorities of intervention and technological shifts through an optimization approach. Moreover, alternative scenarios are developed in order to explore the effects of particular financial and market mechanisms in the electrification of the thermal uses.

The methodological details of the two phases are reported in the followings.

Preparation phase: building stock baseline definition

To develop a mid- and long-term scenario analysis, it is fundamental to define and characterize the baseline condition. The initial preparation phase consisted in the characterization of the current residential building stock, focusing on non-fully electrified uses (i.e. thermal uses: space heating and domestic hot water). To reduce the computational effort of large-scale modelling, the RB approach was deployed to characterize and describe the residential building stock [146, 147]. This phase is divided into the following steps, which will be later discussed in relation to the case study application: i) building stock quantification; ii) RB-based building stock modelling; and iii) RB diversification.

By definition, thanks to the representativeness of the outcomes of the archetype models, the RB-computed results in terms of energy performances of different technological solutions can be considered as representative of a significant portion of the stock [146, 147] and results at single RB level can be extended to broader territorial scales using appropriate multiplication factors (i.e. number of buildings for which the RB is representative, floor area represented by a particular RB). Therefore, the more RBs are appropriately diversified, the wider the range of operational conditions they represent can be. The main outcome of the preparation phase was the definition of a suitable number of RBs to be used as basis for the subsequent scenario analysis, in order to assess the baseline energy consumption and households distribution for the national building stock.

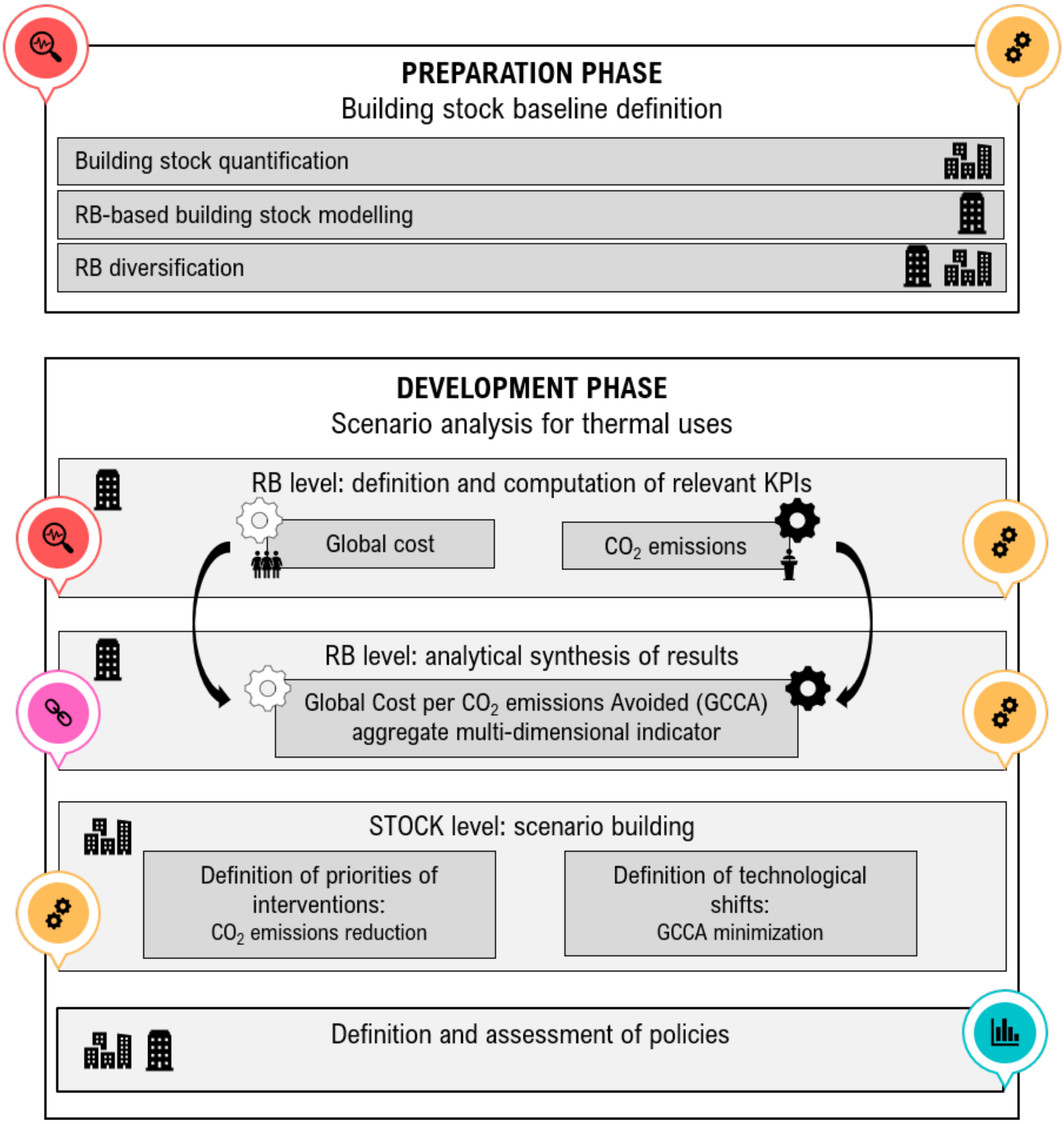


Figure 3.1: Main methodological steps.

Development phase: scenario analysis for thermal uses

This phase consisted in the development of mid- and long-term scenario analyses, aiming to identify possible trajectories of future technological uptake and electrification of the residential thermal uses. The methodological steps of the development phase were computed at two different scales: single RB and stock level (see Figure 3.1). The development phase is structured around four main steps [46]:

- **study and simulate: definition and computation of relevant KPIs**

(RB level). Prior to the scenarios design, it is fundamental to identify and compute the possible indicators that could drive the evolution of the residential sector; this step recalls the application reported in section 2.2.

- **synthesize and simulate: analytical synthesis of results (RB level)**. The identified KPIs are coupled to define the new aggregate multi-dimensional indicator "Global Cost per CO_2 emissions Avoided" (GCCA), to be used as a forecasting tool to reflect consumers' choices in case of retrofit.

- **simulate: technological spreading modelling (STOCK level)**. According to the KPIs assessed for each RB and technological alternative, priorities of intervention in the stock are identified aiming to reduce the buildings environmental impact, while technological shifts are forecasted based on the minimization of the GCCA indicators.

- **simulate and support: definition and assessment of policies**. Specific policy measures are defined and assessed, modifying the GCCA computations at RB level, aiming to evaluate their impacts on the technological uptake evolution of the sector.

Study and simulate: definition and computation of relevant KPIs (RB level) The analysis at RB level recalls the application at micro scale described in section 2.2, aiming to identify and forecast the most competitive technological solutions to be installed within a RB in case of system retrofit. When dealing with the issue of building renovation, to forecast possible future trends, it is fundamental to identify which are the performance indicators that are most likely to drive the choices of the involved stakeholders. In particular, two aspects must be tackled: on which technologies the private stakeholders want to invest and in which direction policy makers want to push their choices [131]. In order to capture both private and public perspectives, the two simple KPIs already discussed in section 2.2 were selected to measure the financial and environmental performances of the technologies under comparison: global cost and CO_2 emissions. However, differently from section 2.2, in this case attention was devoted to the original thermal generator system installed in the RBs in which the retrofit occurs. For this reason, assuming the interest of the public stakeholder to reduce the impact of the existing building stock, the avoided CO_2 emissions guaranteed by a technological solution with respect to the emissions caused by the original RB system were identified as driver towards the electrification from the public standpoint.

The identified simple KPIs were calculated for all the technological alternatives and for each RB across the timespan considered, taking into account the forecasted conditions of the market (i.e. energy prices) and of the power sector towards its progressive decarbonization (i.e. CO_2 emissions factor for electricity).

Synthesize and simulate: analytical synthesis of results (RB level) To compare the alternative solutions in case of retrofit of the thermal generators, the competitiveness was assessed through the definition of a newly-developed aggregate indicator, named “Global Cost per CO_2 emissions Avoided” (GCCA), which is defined as the ratio between the global cost of a specific technological option and the CO_2 emissions avoided thanks to the use of that technology to replace the existing one [46], as shown in Eq. 3.1:

$$GCCA(i)\left[\frac{€}{kg_{CO_2}}\right] = \frac{C_g(i)}{\Delta CO_2(i)} \tag{3.1}$$

where $C_g(i)$ represents the global cost of the i_{th} technological solution and ΔCO_2 represents the quota of emissions saved thanks to the adoption of the i_{th} technological solution with respect to those caused by the original thermal generators installed in the RBs in the baseline.

For each RB, GCCA indicator was deployed to compare different competing technological options available in case of substitution of the space heating (SH) and domestic hot water (DHW) systems, allowing to identify the options able to guarantee the best trade-offs between financial (private driver) and environmental (public driver) aspects, and thus to define the most likely technological shifts in residential buildings, if driven by the minimization of the GCCA indicator [46].

Similarly to what discussed in section 2.2 regarding the GCES aggregate indicator, also GCCA is intended as an indicator of competitiveness of the alternative technologies, aiming to couple in a single metric their financial and environmental performances. However, differently from the GCES, which was intended to compare environmental-friendly solutions with the riskiest in environmental terms to identify the potential risk for the policy makers associated to financially-driven individual choices, in this application attention is devoted to the improvement of the environmental performances of the original RBs. For this reason, the denominator of the indicator was calculated with respect to the environmental impact of the original RB to retrofit, to indicate how much each retrofit solution is able to improve the original environmental performance and thus to award the most effective option. Moreover, if the GCES indicator was not developed in order to identify the investors’ choices, in this case the GCCA was used as a forecasting tool, through which private choices were defined (in case of retrofit), in a hypothetical situation in which their decisions were driven also by environmental benefits. Indeed, the forecasting model developed for studying a possible pathway for the Italian residential sector was built assuming that, in case of retrofit, among all the possible technological alternatives, the private stakeholder would choose the one characterized by the smallest GCCA indicator. Clearly, this condition is true in the assumption that the carbon intensity of the technologies will be used as criterion for the future development of policy actions, in order to further push the market towards the adoption of low-carbon options [46]. Indeed, this scenario advantages the technologies with the lowest GCCA, even if the winning solution could be not the most attractive in financial terms [46].

Simulate: scenario building (STOCK level) The analysis at single RB level, according to which the most beneficial technological alternative can be identified in case of retrofit of the original system, needs to be scaled up to the entire building stock under investigation. To do so, two information are needed: i) the priority of intervention, namely the RBs on which it is fundamental to first intervene; and ii) the technological shift, namely the technological solution to be installed in each RB to retrofit, to reduce its overall impact and increase its energy efficiency. Going into detail, the priority of intervention was defined based on the environmental impact of the existing RBs, according to their original CO_2 emissions; specifically, the higher the emissions of the original RB, the higher the priority of intervention is. The selection of the priorities was performed per each RB class, by comparing the different energy carriers (and thus generation systems) used for meeting their needs. Then, once defined the RB to retrofit, the GCCA-based ranking was used to identify the best technological shift; specifically, for each RB to intervene on, the alternative technological solutions were compared in terms of GCCA indicator, selecting the option with the lowest GCCA.

Based on this assumption, the scenario simulated an hypothetical condition, according to which environmental benefits are effectively translated into financial terms, thus influencing consumers' choices. In other words, the analysis approximates a condition in which the implementation of suitable policies for decarbonization and energy efficiency improvement will be able to effectively drive consumers' choices towards the adoption of more environmental-friendly solutions [46].

To shift from building to stock analysis, proper assumptions in terms of renovation rate are needed, in order to identify the portion of households that undergoes a renovation on each time-span. As a result of this step, the households distributions by generation technology for the entire residential stock for SH and DHW can be estimated, allowing to assess the impacts on consumptions and electrification of the forecasted technological shifts.

Simulate and support: definition and assessment of policies By definition, the lowest the GCCA indicator for a specific RB, the most competitive the technological solution will be. However, as already addressed in section 2.2, the indicators depend on the defined boundary conditions in terms of energy prices, taxes, market mechanisms. Therefore, different alternative policy scenarios were developed, each influencing the global cost computation (e.g. inclusion of environmental taxes, adoption of incentive mechanisms, changes in the contract formulation for the energy cost calculation, etc.). As a consequence, for each alternative scenario, the GCCA indicators of the competing solutions needed to be re-calculated. Even though this step does not influence the identification of the priorities of intervention (based on the environmental impact of the RBs), it may imply the modification of the GCCA-based technological ranking. Furthermore, specific sensitivity analyses on renovation rate and energy prices were developed, in order to assess their influence on the final results.

3.1.4 Case study

The Italian residential building stock was selected as case study [46], in line with the application presented in section 2.2. According to national statistics, residential buildings represent approximately 85% of the total number of buildings in Italy [154] and they offer a higher electrification potential compared to non-residential buildings [46]. The work concentrated on thermal uses (both SH and DHW), being at the same time the most demanding and the least electrified services in the residential sector. Indeed, according to Ref. [169], these uses represent approximately three quarters of the Italian residential demand (68% and 12% for SH and DHW, respectively). Moreover, focusing on the electricity carrier, only 2% and 14% of final energy demand for space heating and domestic hot water, respectively, is electrified [169]. Conversely, space cooling and electrical equipment and lighting are fully electrified uses, while electricity represents almost 15% of the total energy consumption for cooking [169].

Preparation phase: building stock baseline definition

Building stock quantification In order to define the baseline for the subsequent scenario analysis, the first step consisted in the quantification of the residential building stock and in its classification according to the parameters formerly considered in section 2.2: two building typologies (SFHs, MFHs), three periods of construction (“before 1980”, “between 1981 and 2000” and “after 2001”) and five geographical areas (North-West, North-East, Centre, South, Islands), obtaining a total of 30 classes, each associated to a number of households, in line with the last Italian census [154]. In order to characterize each class in energy terms, the RB approach was used.

RB-based building stock modelling In line with the previous application at micro scale, 6 RBs from TABULA database were selected and assumed in terms of geometry, type of energy carrier for thermal uses (resulting to be always gas for the selected RBs) and efficiencies of various sub-systems (emission, distribution, generation) [153], while they were further characterized in terms of envelope thermal properties (please refer to section 2.2 for further details). Energy needs for SH and DHW were obtained through monthly quasi steady-state simulations for the five geographical zones. Then, knowing the sub-system efficiencies from the original RBs, energy consumptions for thermal uses were computed. A total of 30 RBs was firstly considered as representative of the Italian building stock, each characterized by SH and DHW reference energy consumption intensities (expressed in kWh/m^2). Starting from these results and knowing the distribution of households with SH and DHW services within the 30 classes, Eq. 3.2 and 3.3 were used to compute the average stock energy use intensity per each energy carrier:

$$EI_{SH}(j) = \frac{\sum_{i=1}^{30} EI_{SH,RB(i)}(j) \cdot n_{RB(i)}}{\sum_{i=1}^{30} n_{RB(i)}} \tag{3.2}$$

$$EI_{DHW}(j) = \frac{\sum_{i=1}^{30} EI_{DHW,RB(i)}(j) \cdot n_{RB(i)}}{\sum_{i=1}^{30} n_{RB(i)}} \tag{3.3}$$

where $EI_{SH}(j)$ and $EI_{DHW}(j)$ represent the average energy intensity of the j_{th} energy carrier (e.g. gas, biomass, electricity, oil, etc.) for space heating and domestic hot water, respectively, $EI_{SH,RB(i)}(j)$ and $EI_{DHW,RB(i)}(j)$ the energy intensity of the j_{th} energy carrier for space heating and domestic hot water of the i_{th} RB and $n_{RB(i)}$ the number of households represented by the i_{th} RB.

Total SH and DHW energy consumptions were calculated by multiplying the obtained energy use intensities by the total real floor area existing in the baseline year (2015) and the results were compared to national energy statistics. At this stage, since the 6 selected RBs from TABULA database have gas-fuelled systems for both end-uses, an adjustment in terms of technological distribution within the stock was needed, to better align results with national statistics.

RB diversification The adjustment process allows to reduce the deviation between the model-based final energy consumptions per each energy carrier and the information coming from national statistics. To this purpose, the initial set of 30 RBs was diversified in terms of technological distribution, by introducing new RBs. For space heating, in line with Ref. [170], generators supplied by electricity, biomass and oil were added; for domestic hot water, instead, in line with Refs. [171, 172], the existing gas-fuelled generators were re-distributed between gas and electricity vectors. As a consequence, new RBs were simulated, to compute the energy intensities based on the efficiencies of the new generators included in the model. In particular, the original set of RBs was differentiated, varying the efficiencies of the generators (but keeping the other sub-systems efficiencies fixed [153]). Generation efficiencies were assumed referring to TABULA for the most recent periods of construction [153], while for the period "before 1980", efficiencies from updated national regulation [173] were adopted, assuming that, compared to their original status, those buildings would have probably already undergone a substitution of their original generators for both uses.

As a result of this procedure, 120 RBs for SH and 60 RBs for DHW (the thermal uses were separately assessed in this application) were considered, and, based on this, consumptions at stock level were computed adopting Eq. 3.2 and 3.3 and compared with national energy balance statistics for the residential sector [169]. A calibration factor of 1.09 and 1.17 for space heating and domestic hot water, respectively, was calculated as the ratio between statistical data and model results (as in Ref. [174]), meaning that the RB-based model is slightly underestimating the energy consumptions for thermal uses. As shown in Figure 3.2, for SH, natural gas consumption was overestimated with respect to statistical data, even though this is compensated by the slight underestimation of biomass usage (probably due to the fact that the model does not take into account any adoption of secondary energy systems, which are usually biomass-fuelled). The variation between model and statistical values for DHW, instead, is due to the fact that the RB-based model considers only two energy vectors (gas and electricity), against a more variegated situation in the reality.

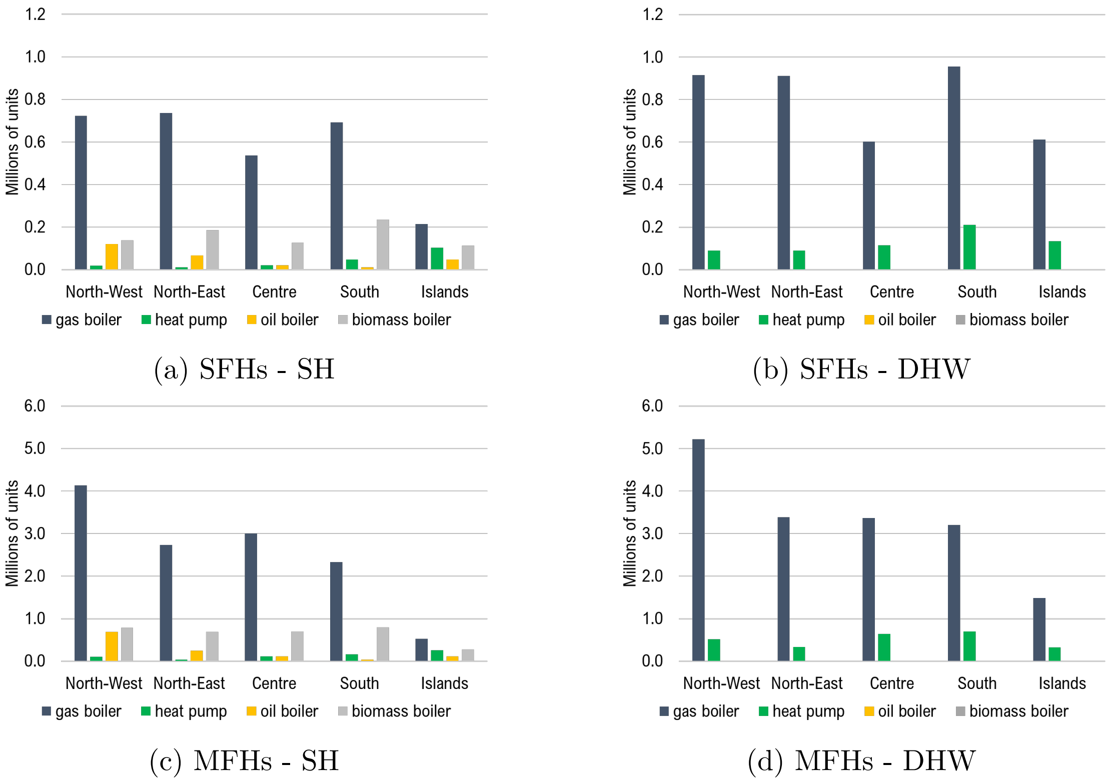
(a) SH (b) DHW

Figure 3.2: Comparison of shares of energy carriers between model (external circle) and statistics (internal circle) [169]: (a) space heating (SH); (b) domestic hot water (DHW).

As a conclusion of the preparation phase, Figure 3.3 shows the households distribution by generation technology for the two thermal uses resulting from the adjustment process. The represented distributions were used as the starting point for the subsequent scenario analyses.

Development phase: scenario analysis for thermal uses

This step aimed to develop a scenario analysis to forecast the technological trends of residential thermal uses for 2030 and 2050, by assessing diverse competing technological options, when a system retrofit occurs. Specifically, the most likely technological shifts in residential buildings were identified for each RB according to the aggregate GCCA indicators, identifying the solutions able to minimize the emission abatement cost. Computations at RB level in terms of energy intensities were then



(a) SFHs - SH
(b) SFHs - DHW
(c) MFHs - SH
(d) MFHs - DHW

Figure 3.3: Households distribution by generation technology and geographical area for 2015, for SH and DHW.

scaled up to the overall stock, considering a fixed annual renovation rate over the entire timespan.

Computation at RB level The analytical approach at RB level was based on the comparison of diverse technological solutions on the basis of their global cost and their potential to reduce the CO_2 emissions with respect to the original installed generation systems, foreseeing future trends through the assessment of the GCCA indicators. In this application, a technological-oriented study was developed, assuming to intervene on the sole supply technologies of the RBs, by substituting the existing energy systems with more efficient options. Starting from the energy needs of the original set of RBs (simulated using Masterclima), the energy consumptions associated to the new alternative generators were computed varying the original generation efficiencies, while keeping fixed the other sub-systems efficiencies (emission and distribution), in line with the RBs information gathered from Ref. [153]. The calculation procedure recalls the micro scale application presented in section 2.2. Three technologies for space heating were considered (i.e. condensing gas boiler, biomass boiler and electric heat pump), while the electric boiler option was added for domestic hot water production. The alternative technological solutions are reported in Table 3.1, summarizing the main assumptions in terms of generation efficiencies and financial parameters useful for the calculation of their global costs (i.e. investment costs, defined according to market prices, and maintenance costs, gathered from Ref. [150]). A useful life of 20 years was assumed for the entire set of technologies [150].

Table 3.1: Techno-economic parameters of the technological options for intervention on thermal uses energy systems.

Technology	**Generation efficiency** [-]	**Investment cost** [€/kW]	**Annual maintenance cost** [%]
Condensing gas boiler	0.96	100-137	1.5
Biomass boiler	0.88 - 0.89	460-570	2.0
Electric air-to-water heat pump	3.80 - 4.10	580-644	3.0
Electric boiler	0.95	90	1.0

Assumptions in terms of energy prices and tariff schemes were identical to the application of section 2.2. It has to be noted that the non-progressive tariff for heat pumps, in force in 2015 for buildings with autonomous systems having heat pumps has sole heating system, was not valid for DHW. Therefore, this tariff scheme (when convenient) was applied only to SH systems (please refer to section 2.2 for more details). A 5% interest rate was used for the global cost calculation.

Based on these assumptions, KPIs were calculated for 2030 and 2050 for each RB, varying the boundary conditions (energy prices and CO_2 emission factors for electricity), in line with Refs. [157, 158] and with the previous application.

Computation at STOCK level Once defined the reciprocal competitiveness among the solutions to be potentially installed in each RB according to the GCCA-based ranking, results at single RB level were scaled up to the entire stock. To this purpose, the environmental KPI (CO_2 emissions) was used in order to identify the priorities of interventions within the overall stock, meaning that, for each construction period, building typology and location, the RB with the highest CO_2 emissions was selected as the first to intervene on. Then, the scenario was based on the GCCA minimization approach, according to which the GCCA values were used as measures of competitiveness to identify the best technological shift. Specifically, for each previously selected RB to retrofit, the technological shift was defined on the basis of the alternative with the lowest GCCA among the set of solutions at disposal.

A 1.5% annual renovation rate and a 1% annual new construction rate [48] was considered for the analysis, while demolition was not accounted. Moreover, the following constraints were fixed [46]:

- a unique generator substitution over the entire period was assumed;
- the dismission of oil generators by 2030 was hypothesized;
- the thermal uses in new buildings were assumed to be electricity-fuelled (and provided by heat pumps).

Definition and assessment of policies In line with the analysis reported in section 2.2, five alternative policy scenarios were modelled (INCR, INC, TF, TXC and TXPM), to test and explore the effects of specific measures on the GCCA-based technological rankings and on the stock-level technological uptake trends. The main assumptions of these scenarios are summarized in Table 2.14. It is important to cite that, differently from SH service, DHW-related indicators are not affected by all scenarios; indeed, for DHW, only electric heat pumps have access to existing incentive mechanisms and, thus, according to their definition, INC and INCR scenarios results are identical for this thermal use.

3.1.5 Key findings and discussion

Based on the assumptions previously described, a first scenario (named BASE) was built. In particular, according to the GCCA-based technological ranking, it was possible to forecast the households distribution by generation technology for the thermal uses in 2030 and 2050, as reported in Figure 3.4 and Figure 3.5 for space heating and domestic hot water, respectively.

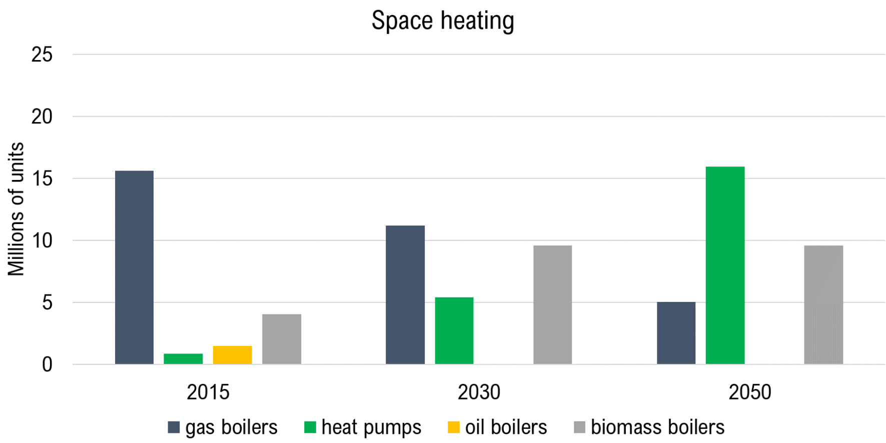


Figure 3.4: Households distribution by generation technology for SH in 2015, 2030 and 2050.

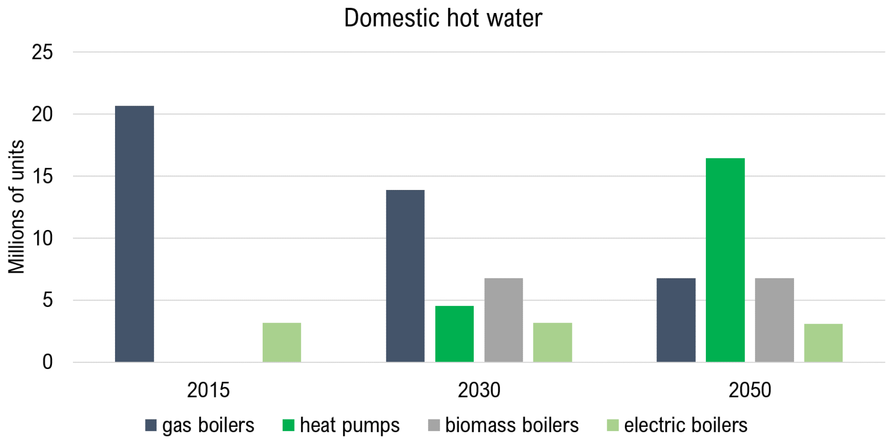


Figure 3.5: Households distribution by generation technology for DHW in 2015, 2030 and 2050.

The number of households with electric technologies for thermal uses is expected to increase, especially in 2050. According to the BASE scenario, in 2030, the biomass boiler results the most beneficial solution for many RBs, while heat pumps share increases in 2050, also supported by the energy prices evolution for the two carriers. Generally, the margin of competitiveness lies in the comparability between biomass and electric solutions, due to the lower consumptions guaranteed by heat pumps (thanks to higher efficiencies) and the lower environmental impact of biomass solutions (thanks to a lower CO_2 emission factor in 2030). Electric heat pumps, mainly in 2030, are still disadvantaged by high electricity prices and higher investment costs. Moreover, as clearly visible in Figure 3.4 and Figure 3.5, households equipped with gas technologies are expected to decrease in both thermal uses, penalized by their bad performances in environmental terms (despite their financial attractiveness in terms of global cost), which result in their exclusion from the GCCA-based technological competition.

Based on the obtained distribution, energy intensities were computed according to Eq. 3.2 and 3.3 and total energy consumptions for the thermal uses in 2030 and 2050 were obtained, considering the variation of the residential floor area due to new constructions. Figure 3.6 shows the evolution of the final energy consumption for the thermal uses from 2015 to 2050 for the BASE scenario. In particular, an electricity share (defined as the ratio of the electricity consumption over the overall energy consumption) of 17.3% is reached, with respect to the initial 2.6% of the baseline year.

The findings so far reported are related to the reference scenario BASE, which evolution is strongly dependent on the GCCA indicators, in turn influenced by the established boundary conditions. Therefore, five alternative policy scenarios were considered, to provide some suggestions on how current or innovative policy

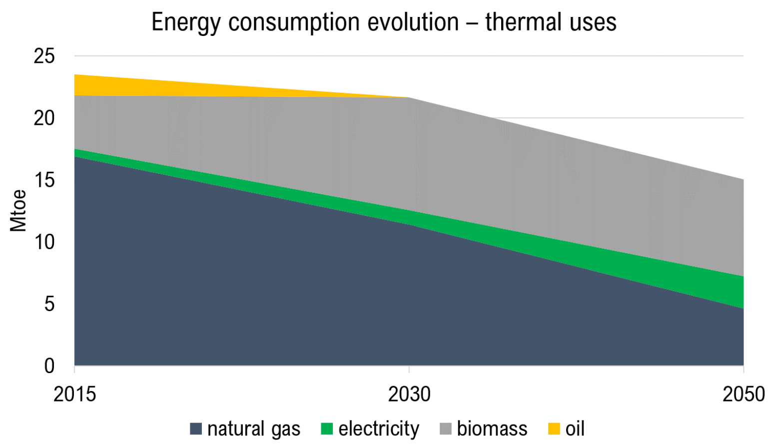


Figure 3.6: Final energy consumption evolution up to 2050 for thermal uses according to the developed model.

schemes could further push the electrification of thermal uses. By definition, the variations of the GCCA indicator associated to the policy scenarios are strongly dependent on those of the global costs, being the denominator fixed by the operational conditions (i.e. CO_2 emissions are not dependent on the alternative policy scenarios). For the sake of exemplification, the variation of global costs and GCCA indicators induced by the alternative policy measures is reported for the MFH built before 1980, located in North-West and having gas as energy vector for both thermal uses in the original RB. More precisely, Figure 3.7 and Figure 3.8 shows the variations of the global cost caused by the alternative policy scenarios for all the technological alternatives considered for the retrofit of the generators, for SH and DHW, respectively.

Starting from SH (Figure 3.7), it is possible to see that biomass and gas boilers present similar global costs in 2030, while heat pump appears to be always the most expensive solution (the same results were discussed in the graphical tool of Figure 2.20 in section 2.2). In 2050, instead, biomass boiler is disadvantaged by the energy prices variations. The global cost of the technological solutions is differently influenced by the policy scenarios. Indeed, gas technologies are only affected by INCR scenario, which considers the adoption of incentive mechanisms also for condensing gas boilers, thus reducing the global cost of the technology. The solution is slightly affected by TXC and TXPM scenarios, both inducing an increment of the global cost due to the taxation on CO_2 and PM emissions, respectively. Similar considerations can be done for the biomass technology, with the most significant variations obtained for INCR (-11%) and TXPM (+17%) scenarios. Conversely, the global cost of the heat pump solution is more variable; specifically, three scenarios are able to induce global cost reductions (TF, INC and INCR), while TXC

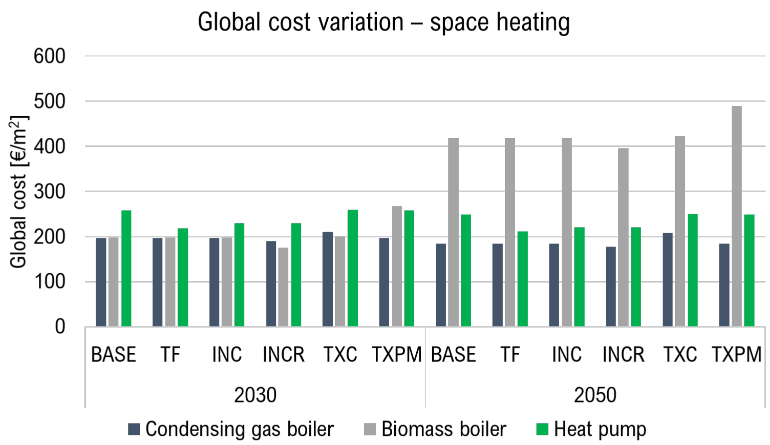


Figure 3.7: Global cost variations for BASE and alternative policy scenarios for 2030 and 2050 for space heating: MFH built before 1980, North-West, gas as original carrier.

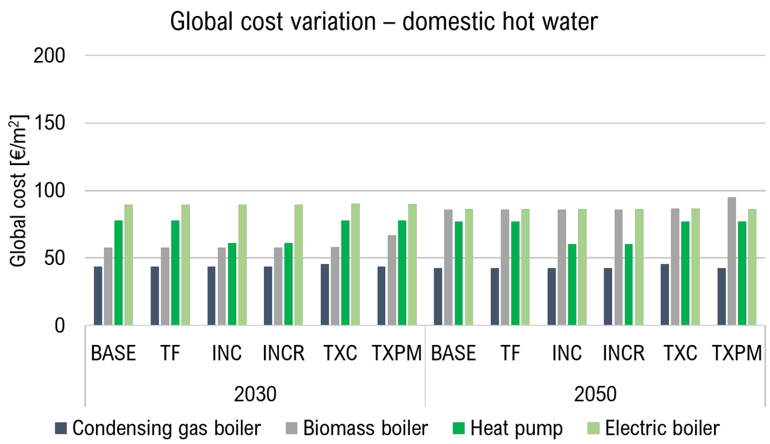


Figure 3.8: Global cost variations for BASE and alternative policy scenarios for 2030 and 2050 for domestic hot water: MFH built before 1980, North-West, gas as original carrier.

and TXPM both cause global cost increments, as for the other two competing solutions. The situation is similar for DHW (Figure 3.8); in this case, it is important to remember that gas, biomass and electric boilers are excluded from incentive mechanisms, and thus their global costs are not modified by INC and INCR assumptions. TF scenario, even though it considers the abolition of the non-progressive tariff for electricity also for the DHW service, does not have effect on the overall results; indeed, since the DHW consumptions for all RBs are low, the tariff envisaged in the TF scenario is identical to the scheme already selected for the computation of the energy cost in the BASE scenario.

As mentioned, based on the GCCA definition, the condensing gas boiler is always excluded from the competition; indeed, this solution is characterized by relatively small CO_2 savings with respect to the original RBs, even though this solution is often the most financially attractive (i.e. with the lowest global cost). Therefore, for all RBs, competitiveness exists between electric and biomass technologies, depending on the operational context (i.e. RBs) and on the boundary conditions (i.e. investment cost, energy costs, etc.). To graphically represent this reciprocal competitiveness, similarly to section 2.2, Figure 3.9 and Figure 3.10 reports the variations in terms of GCCA indicators perceived by the two technologies, in terms of $\Delta GCCA$ among biomass boiler (B) and heat pump (H), calculated as in Eq. 3.4:

$$\Delta GCCA = GCCA_B - GCCA_H \tag{3.4}$$

A negative value corresponds to a greater advantage of the choice of biomass, while a positive $\Delta GCCA$ reflects the convenience of the electric technology over biomass. In 2030, for the space heating service, scenarios TF, INC and TXPM are able to induce a competitiveness variation with respect to BASE, ranking heat pump as the GCCA-based optimal solution for the analysed RB. Differently, for the same year, for domestic hot water service, only INC and INCR scenarios are able to induce this change (since electric heat pump is the only technology for DHW service having access to the incentive mechanisms). In 2050, for both services, heat pump is always preferred, already in the BASE scenario, due to the energy prices projections for both energy carriers [157, 158].

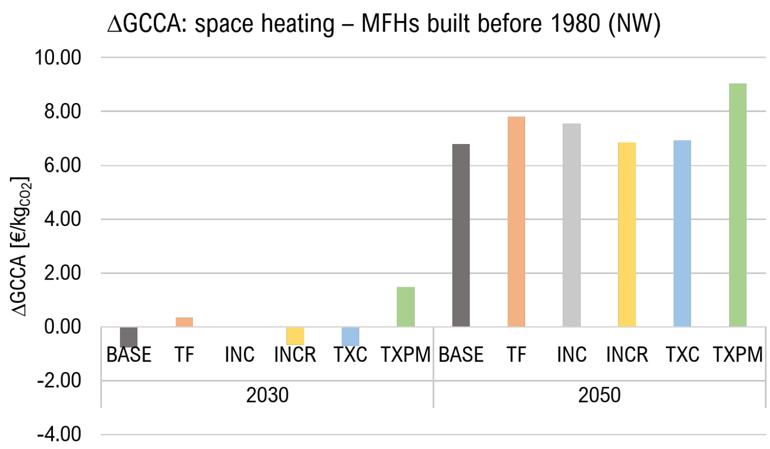


Figure 3.9: $\Delta GCCA$ between heat pump and biomass boiler for BASE and alternative policy scenarios for 2030 and 2050 for space heating: MFH built before 1980, North-West, gas as original carrier.

To evaluate the effects that the alternative policy scenarios can have on the energy consumption evolution of the residential stock, and mainly on the electricity share, Figure 3.11 shows the electrification potential in 2030 and 2050 for the

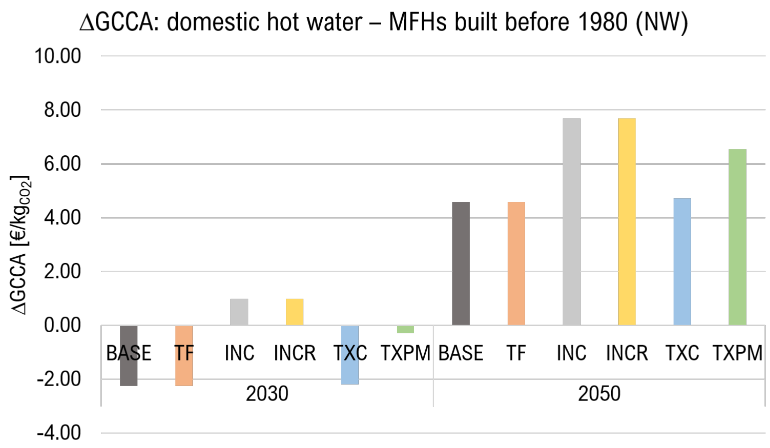


Figure 3.10: $\Delta GCCA$ between heat pump and biomass boiler for BASE and alternative policy scenarios for 2030 and 2050 for domestic hot water: MFH built before 1980, North-West, gas as original carrier.

thermal uses (space heating and domestic hot water), for all the policy scenarios compared to BASE.

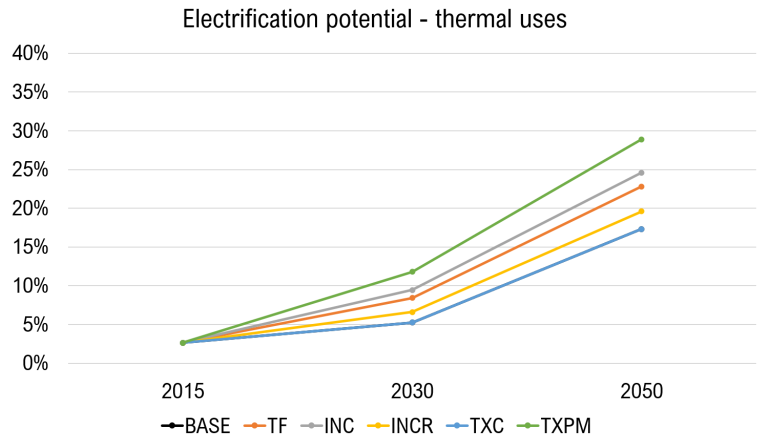


Figure 3.11: Electrification potential in 2030 and 2050 for thermal uses for the alternative policy scenarios.

Only TXC scenario has no effect on the electrification potential (TXC and BASE curves are overlapping); this is due to the fact that, based on the GCCA calculation, the competition exists between biomass boiler and electric heat pump, and both technologies emit low amounts of CO_2 emissions. Therefore, the introduction of an environmental taxation on the CO_2 emissions generated by these technologies does not change the competitiveness between them, not affecting the scenario building up to 2050. Differently, all other policy scenarios generate some variations in terms of electrification potential compared to BASE. The highest effect is obtained by the TXPM scenario (29% electrification), which foresees the introduction of the environmental taxation on PM emissions; this tax disadvantages the biomass boiler (due to its high generated PM10 emissions), favouring the diffusion of the electric solution already in 2030. INC and TF scenarios both guarantee high electrification potentials (25% and 23%, respectively), since they both consider measures only affecting the heat pump solution, favouring its diffusion against the biomass boiler. Finally, INCR scenario, which reflects the real deployment of incentive mechanisms for all the considered technologies, slightly favours heat pump over biomass boiler, already in 2030, but it reduces the potential of electrification to 20% in 2050.

Table 3.2 reports the same results for the separated thermal uses. If the aforementioned trend is visible for space heating, a different situation occurs considering the sole DHW. In this latter case, as previously mentioned, the sole INCR and INC scenarios have effects on the results. All other scenarios, instead, do not induce any significant variation on the BASE results. As for the scenarios considering the introduction of environmental taxes, differently from space heating, TXPM has almost a null effect, due to the low energy consumption for this end-use, which contributes to lower the taxation effect on the biomass/heat pump competitiveness. In line with the values reported in Table 3.2, it is clear that the overall electrification of both thermal uses is dependent on the evolution of the SH electrification share, while DHW has a lower effect on the total results (due to the lower energy consumptions at stake).

Table 3.2: Share of electricity consumption for space heating and domestic hot water for all the policy scenarios in 2015, 2030 and 2050.

Final use	**Milestone**	**BASE**	**TF**	**INC**	**INCR**	**TXC**	**TXPM**
SH	2015	1%	1%	1%	1%	1%	1%
	2030	3%	7%	7%	4%	3%	11%
	2050	15%	21%	21%	16%	15%	28%
DHW	2015	14%	14%	14%	14%	14%	14%
	2030	18%	18%	27%	27%	18%	18%
	2050	33%	33%	51%	51%	33%	35%

Complete scenario analysis for all final uses

In order to provide a complete vision of the residential sector and of its possible pathway up to 2050, the analysis was extended to all final uses, including cooking, space cooling, appliances and lighting to the detailed modelling of the thermal uses. Two simplified sub-models were introduced to assess the other end-uses, in addition to the optimization approach (i.e. minimization of the GCCA indicator) deployed for the thermal uses. Specifically, for cooking, all new buildings were assumed to be equipped with induction stoves (in line with the approach used for the thermal uses); for existing buildings, instead, the installation of electricity-fuelled stoves was hypothesised concurrent with the electrification of SH and DHW end-uses. For the other final uses (i.e. space cooling, appliances and lighting), their baseline energy consumptions were projected based on historical trends; moreover, in order to consider the effect of energy efficiency policies on these uses, the projected consumptions were adjusted according to the "energy efficiency index" (ODEX [175]). The assessment of these services is simplified, especially regarding space cooling, which demand is significantly increasing in the last years. Therefore, a more detailed evaluation of the energy consumption for cooling could be developed in future work.

To sum up, each cluster of end-uses assessment was separately evaluated and the results were then combined to compute the overall residential sector consumptions in 2030 and 2050. Figure 3.12 reports the evolution of the energy consumption of the entire Italian residential sector up to 2050, showing a 29% reduction from 2015 to 2050. The details per each milestone are reported in Figure 3.13. The so-built scenario allows to forecast a 76% reduction of CO_2 emissions and a 31% reduction of PM emissions in 2050 (with respect to 2015 values).

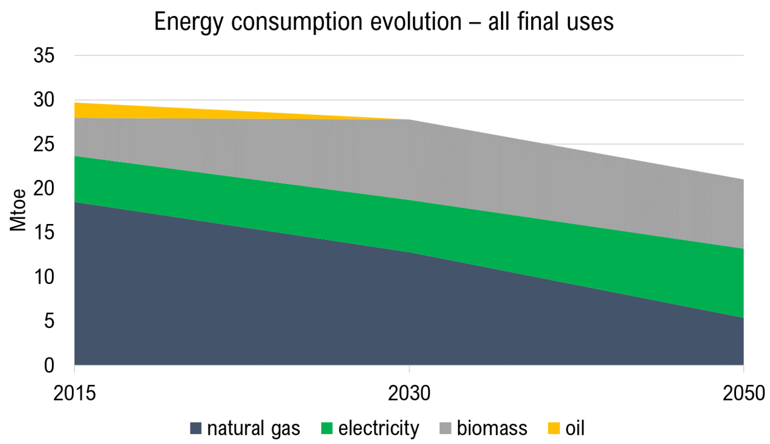
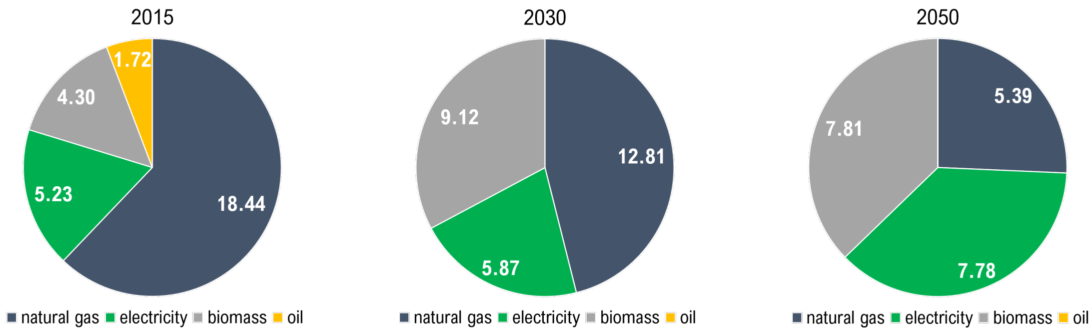


Figure 3.12: Energy consumption evolution up to 2050 for the overall residential sector.



(a) 2015 (b) 2030 (c) 2050

Figure 3.13: Energy consumptions by fuel in 2015, 2030 and 2050 for the overall residential sector [Mtoe].

In 2050, a total 37.1% electrification potential is estimated (21.1% in 2030), with respect to the initial 17.6% in 2015 [1]; the details by end-use are reported in Table 3.3.

Table 3.3: Electrification per final use in 2015, 2030 and 2050 for residential buildings. SH = space heating, DHW = domestic hot water, CK = cooking, SC = space cooling, LA = lighting and appliances.

Milestone	SH	DHW	CK	SC	LA	TOTAL
2015	1%	14%	15%	100%	100%	18%
2030	3%	18%	24%	100%	100%	21%
2050	15%	33%	51%	100%	100%	37%

Moving to the policy analysis, Figure 3.14 shows the electrification potential in 2030 and 2050 for the overall residential sector for the different policy scenarios. A variation of the percentage of electricity over the final energy consumption up to 49% (TXPM scenario) is visible, with respect to the reference value of 37% reached for the BASE scenario. As expected, the electrification trend reflects the one obtained for the sole thermal uses, with the highest variations induced by TXPM (49%), INC (45%) and TF (43%) scenarios.

Figure 3.15 reports the energy consumption by fuel in 2015, 2030 and 2050 and for the different scenarios, shown in crescent order in terms of electricity share. The representation helps visualizing how the increments of electricity consumption due to the diverse policy measures correspond to decrements of biomass consumption,

[1]Due to later updates in the Odyssee-Mure platform, by performing the analysis considering the statistics of electricity consumption currently available in the platform as input for the baseline characterization, the trend would be confirmed (18.3% in 2015, 21.3% in 2030 and 37.4% in 2050).

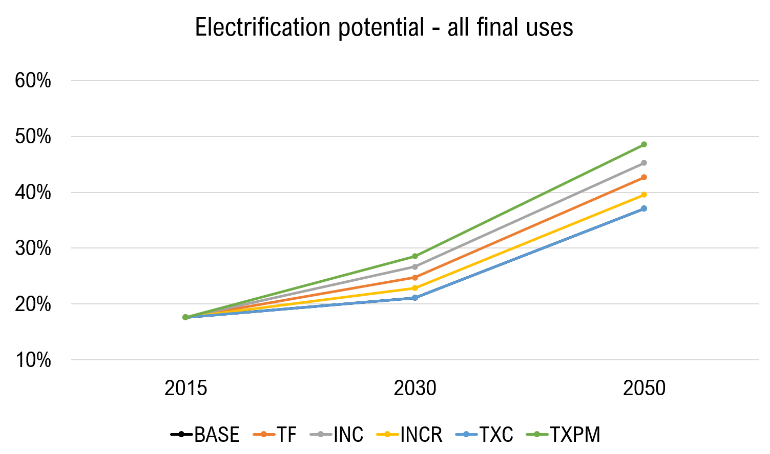


Figure 3.14: Electrification potential in 2030 and 2050 for the overall residential sector for the alternative policy scenarios.

thus highlighting how the GCCA-based scenarios experience a competition only between biomass boiler and heat pump, while the quota of gas consumption is almost constant in all scenarios for the same timespan.

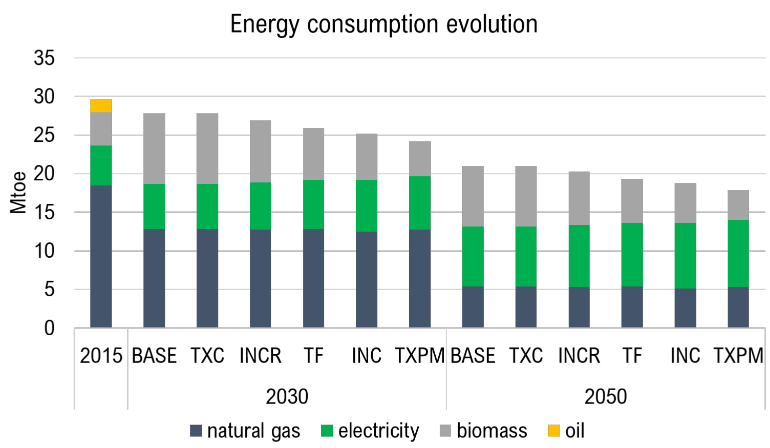


Figure 3.15: Energy consumption evolution in 2030 and 2050 for the overall residential sector for the alternative policy scenarios.

Coming to environmental aspects, Figure 3.16 shows the evolution of the CO_2 emissions caused by the whole Italian residential sector, starting from the 2015 value, for the alternative policy scenarios. No significant variations are experienced among the scenarios, since the developed GCCA-based optimization model forces the adoption of the solutions with the lowest GCCA indicators, thus with high savings in terms of CO_2 emissions. Indeed, as previously commented, when a retrofit occurs, the competition exists between heat pump and biomass boiler, and both technologies are targeted as environmental-friendly, independently on the type of policy measure considered. Moreover, the priority of retrofit intervention within the stock is defined based on the original environmental impact of the single RBs, thus prioritizing the renovation of the most impacting RBs (i.e. oil- and gas-fuelled RBs). Therefore, comparable reductions are forecasted for the different models, with slight differences among them. Specifically, a 76% reduction is guaranteed by BASE scenario, while the alternative scenarios allow this reduction to range between 76% (TXC) and 78% (TXPM and INC).

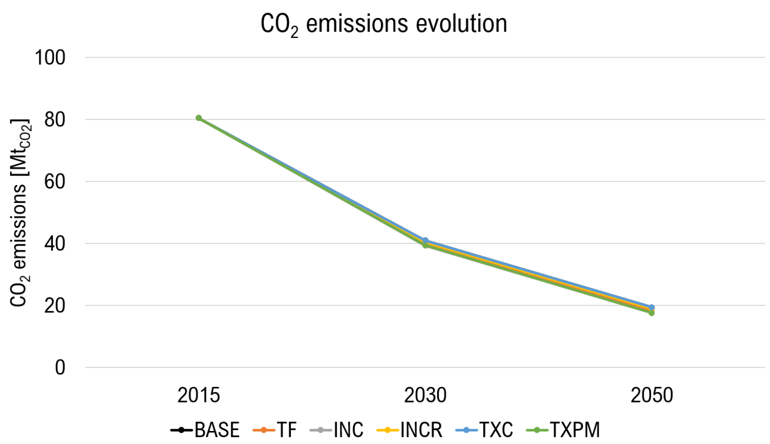


Figure 3.16: CO_2 emissions evolution up to 2050 for the overall residential sector for the alternative policy scenarios.

A different situation is highlighted when considering the trend of PM emissions. In this context, an initial consideration is due. Indeed, it is important to specify that PM emission factors were individually calculated and tailored depending on the assessed scenario. PM emission factors were differentiated between existing and newly-installed biomass boilers, in order to take into account the progressive improvements of filtering techniques, which helps reducing the impact of these systems in terms of air pollutant emissions (e.g. PM, NO_x, SO_x, etc.). For this reason, a 95 g_{PM}/GJ emission factor was associated to new biomass boilers, while a 480 g_{PM}/GJ to existing ones [160]. Therefore, differently from what done in terms of CO_2 emissions, PM emission factors were dependent on the specific scenario (i.e. linked to the forecasted diffusion of new biomass boilers, according to the GCCA-based ranking). In order to evaluate the emissions generated by the different scenarios, an average PM emission factor was calculated per each scenario, weighting the previously-mentioned factors by the number of associated technologies in each milestone year. The trend of the weighted PM emission factors is reported in Figure 3.17 for the different scenarios, while the obtained PM emissions evolutions are reported in Figure 3.18.

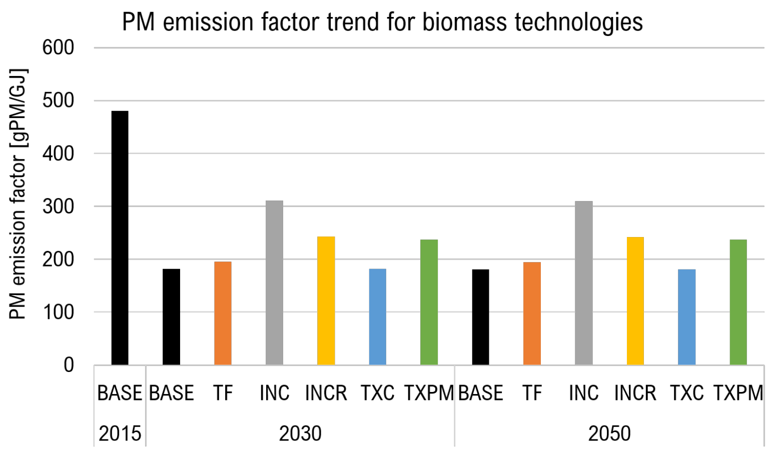


Figure 3.17: PM emissions factor trends up to 2050 for the alternative policy scenarios.

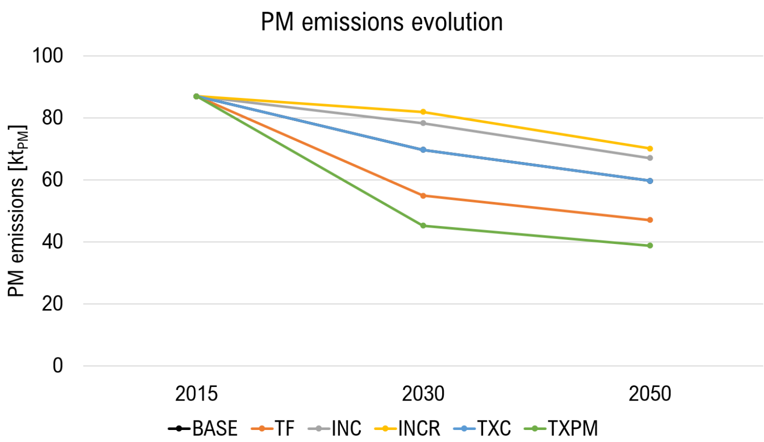


Figure 3.18: PM emissions evolution up to 2050 for the overall residential sector for the alternative policy scenarios.

The local environmental impact of the sector is strictly dependent on the diffusion of the biomass technology, being it the strongest contributor to the PM emissions. In particular, the higher the number of newly installed biomass units, the lower the associated PM emission factor is (as visible for BASE and TXC scenarios in Figure 3.17); this is due to the fact that these scenarios forecast a greater diffusion of new biomass boilers in 2030, in turn inducing a decrement of the emission factor; conversely, scenarios that forecast a lower uptake of biomass technologies (favouring the electric solutions already from 2030) result in higher emission factors (due to the higher weight of old biomass technologies with respect to the better performing ones). PM emissions trends reported in Figure 3.18, thus, are dependent on the calculation of the emission factors, disadvantaging, for instance, INC and

INCR scenarios, which foresee a stronger diffusion of electric technologies already from 2030, in place of biomass ones, in both thermal uses. Also in this case, the best results in terms of emissions reduction are achieved by TF and TXPM scenarios, thanks to the beneficial combination of a more controlled diffusion of biomass technologies in 2030 for both thermal uses and the progressive uptake of electric solutions for SH. In these cases, lower PM emissions factors (if compared to INC and INCR scenarios) are related to the fact that TF and TXPM scenarios are solely affecting the space heating end-use, while biomass boilers are still advantageous for DHW. Conversely, INC and INCR scenarios affect both thermal uses, advantaging heat pumps for both SH and DHW services.

So far, the considered policy measures were separately and alternatively evaluated in comparison to the BASE scenario; in particular, according to the developed model, the scenarios with the greatest effects in energy and environmental terms are TXPM, TF and INC. In order to provide forecasts of future compresence of alternative measures, four additional scenarios were developed, each representing a combination of the previously analysed models: 1) COMB1 considers the combination of TF and INC; 2) COMB2 the combination of TF and INCR; 3) COMB3 the combination of TXPM and INC; and 4) COMB4 the combination of TXPM and INCR. The results achieved in terms of electrification potential and energy consumption reduction are reported in Figure 3.19 and Figure 3.20, respectively. The reduction of final energy consumption of the combined scenarios is compared with the variations induced by BASE, TXPM, TF, INCR and INC scenarios, when separately assessed.

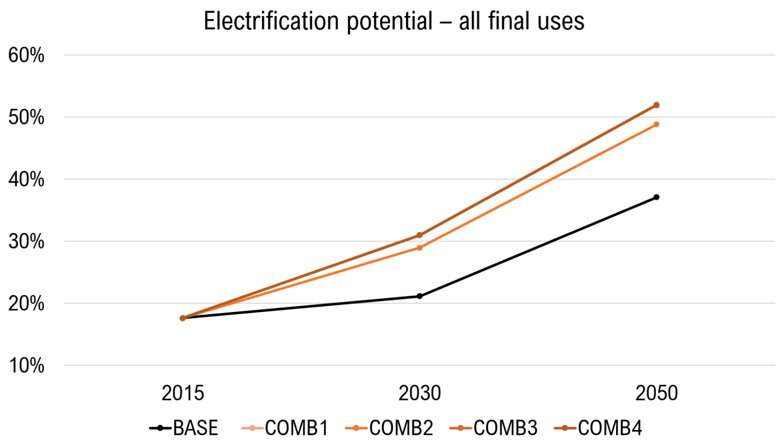


Figure 3.19: Electrification potential in 2030 and 2050 for the overall residential sector for the combined alternative scenarios.

COMB1 scenario (combination of TF and INC scenarios) achieves the highest percentage of electrification rate in 2050 (equal to 52.1%), even though a similar outcome is reached with COMB3 (TXPM+INC) and COMB4 (TXPM+INCR),

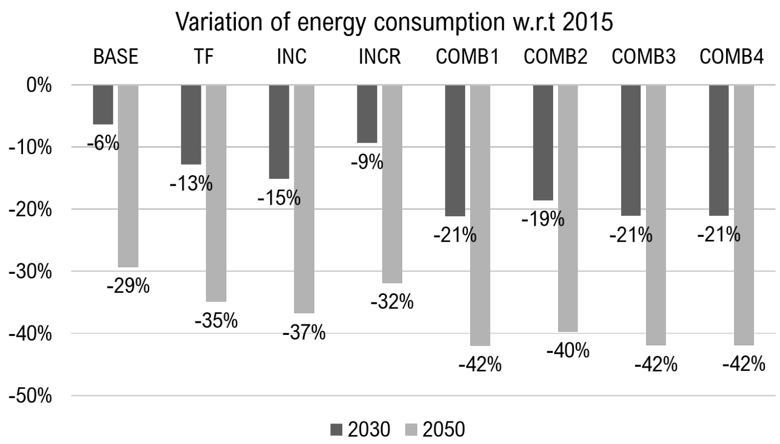


Figure 3.20: Variation of energy consumption in 2030 and 2050 (w.r.t 2015) for the overall residential sector for the alternative scenarios.

achieving both an electrification rate of approximately 52%. The same consideration is visible in terms of total energy consumption reductions. This is due to the fact that the policy measures combinations are able to equally push the market towards the diffusion of electricity-based technologies in place of biomass already from 2030. Conversely, COMB2 (TF+INCR) scenario obtains a slightly lower energy consumption reduction and electrification rate (48.8%), since, in this case, the INCR scenario still advantages the biomass boiler. The effect of INCR in COMB4, instead, is lower, due to the strong effect induced by the TXPM measure in the competitiveness between heat pump and biomass boiler, which, alone, is able to exclude biomass from the competition (despite the incentive mechanisms).

Sensitivity analysis

The renovation of the existing building stock has acquired a significant relevance in recent years, due to the current inefficiency of existing buildings and low rates of energy intervention [53]. This section aims to estimate the effect that the renovation rate assumption may have on the reduction of national-based energy consumptions and emissions and on the electrification potential. Specifically, starting from the previous findings, a sensitivity analysis on the annual renovation rate at stock level was developed, running the BASE scenario considering a lower (0.5%) and a higher (2.5%) annual rate with respect to the initial assumption of 1.5% [48]. The range of renovation rates represents the average range for European Union, with the Italian situation being in the middle (1.2% rate) [48].

Table 3.4 summarizes the energy consumptions by fuel for the BASE scenario (no policy measures considered), assuming the three renovation rates (being the new construction rate always the same, and equal to 1%), while Figure 3.21 shows the total energy consumption variations for the three scenarios, with respect to 2015.

Table 3.4: Energy consumption by fuel in 2015, 2030 and 2050 for the overall residential sector [Mtoe].

Scenario	**Milestone**	**Natural gas**	**Electricity**	**Biomass**	**Oil**	**Tot**
BASE	2015	18.44	5.23	4.30	1.72	29.69
	2030	12.81	5.87	9.12	0.00	27.80
	2050	5.39	7.78	7.81	0.00	20.98
BASE 0.5%	2030	15.82	5.85	6.18	0.00	27.84
	2050	11.66	6.86	5.29	0.00	23.81
BASE 2.5%	2030	9.54	5.85	12.46	0.00	27.86
	2050	0.76	8.41	8.79	0.00	17.96

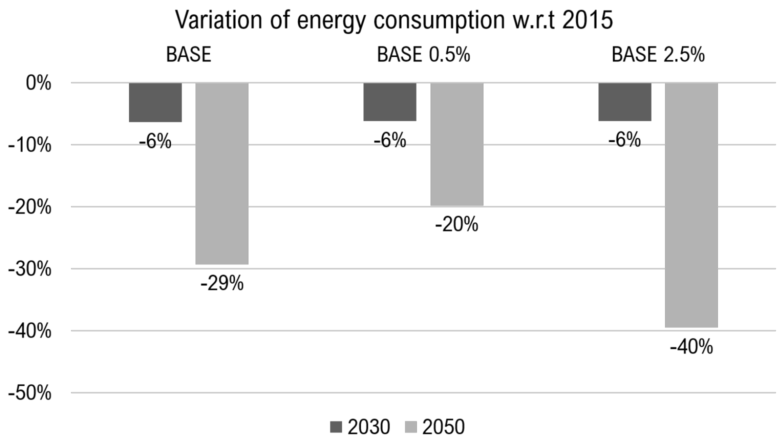


Figure 3.21: Sensitivity analysis on renovation rate: variation of energy consumption in 2030 and 2050 (w.r.t 2015) for the overall residential sector.

In 2030, the share of natural gas consumption decreases from 57% to 34%, moving from a 0.5% to a 2.5% rate, while biomass increases its share (due to the higher spreading of biomass technologies in 2030, according to the BASE GCCA-based conditions); electricity consumption, instead, remains almost constant in the scenarios. A different situation occurs in 2050, when, as expected, the spreading of electric technologies (preferred to biomass ones, due to the energy prices evolution) is stronger in the scenarios with higher renovation rates. The gas share is reduced from almost 50% in the BASE 0.5% scenario to approximately 4% in the BASE 2.5% scenario. Biomass share slightly increases from 2030 to 2050 (more in the BASE 2.5% scenario), but the highest variations are experienced by the electricity vector, resulting in a 47% electrification rate for the BASE 2.5% scenario (compared to the 37% of the BASE scenario), with respect to the 29% obtained in the BASE 0.5% scenario. Figure 3.22 graphically reports the results in terms of electrification rate for the three scenarios, showing a similar trend until 2030 and a greater differentiation up to 2050.

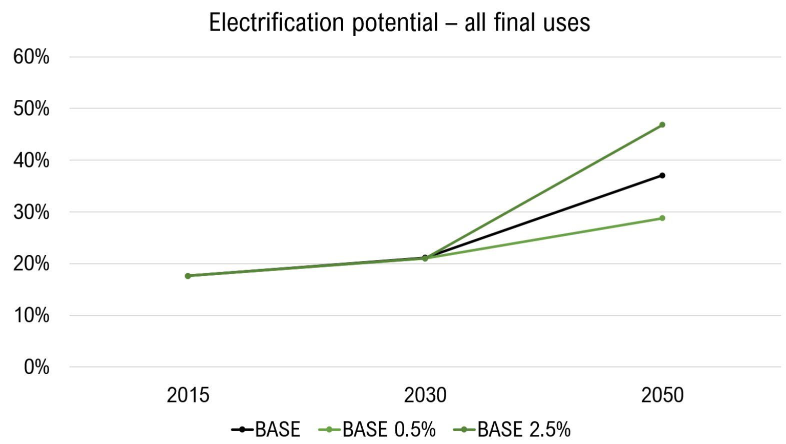


Figure 3.22: Sensitivity analysis on renovation rate: electrification potential in 2030 and 2050 for the overall residential sector.

Finally, in order to assess the contribution of energy prices to the overall results, a sensitivity analysis was developed for the biomass vector, considering increasing energy prices from 2015 to 2050, differently from the initial assumption (according to which biomass energy price is constant until 2030 and then increases between 2030 and 2050 [158]). The results in terms of electrification rate are reported in Figure 3.23, according to which a clear competition between biomass boiler and electric heat pump is visible already from 2030, showing a higher electrification rate also from this year (26% in 2030 and 45% in 2050, compared to the BASE results of 21% in 2030 and 37% in 2050). This scenario leads to an overall 37% reduction of final energy consumption in 2050 (comparable to that achieved by the TXPM scenario), as well as a 78% and a 50% reduction of CO_2 and PM emissions, respectively, in 2050 (with respect to 2015 values).

3.1.6 Focus box: indicators to estimate the impact of electrification on energy transition

Energy scenarios are usually compared and assessed by means of common energy metrics, among which total final consumption (TFC), total primary energy supply (TPES), energy and carbon intensity and environmental indicators. In this section, in the light of the "electricity triangle" concept previously introduced in Chapter 1.2, attention is devoted to the assessment of the contribution of electrification to the variation of these traditional multi-dimensional KPIs on the mid- and long-term, as developed in Refs. [41, 46]. The methodological framework conceptualized

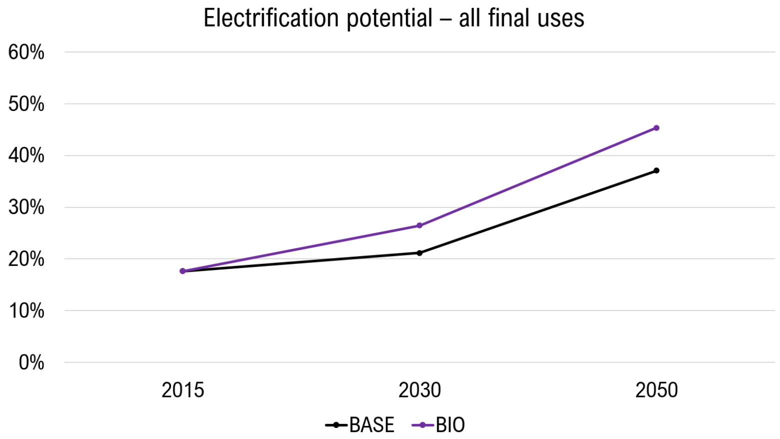


Figure 3.23: Sensitivity analysis on biomass energy price: electrification potential in 2030 and 2050 for the overall residential sector.

in Bompard et al.'s work [46] and reported also in Ref. [41] is here exemplified for the sole building sector, which represents the focus of this chapter.

The methodological framework is based on the assessment of the contribution of electrification to the total energy consumption variation obtained from the previous scenario analysis, in each milestone year t (2030 and 2050) with respect to the baseline year t_0 (2015) [46].

The overall final energy consumption at the year t can be defined as in Eq. 3.5:

$$TFC_t = (TFC_{el}^{t_0} + \Delta TFC_{el}^{t}) + \sum_j (TFC_j^{t_0} + \Delta TFC_j^{t}) \tag{3.5}$$

where $TFC_{el}^{t_0}$ represents the electricity consumption in the baseline year t_0, ΔTFC_{el}^{t} the variation of electricity consumption at the milestone year t with respect to the baseline year t_0, $TFC_j^{t_0}$ represents the consumption of the j_{th} non-electrical commodity in the baseline year t_0 and ΔTFC_j^{t} the variation of the j_{th} non-electrical commodity consumption at the milestone year t with respect to the baseline year t_0.

To estimate the contribution of electrification to the overall KPIs variation, it is important to assess the different factors influencing the variation of energy consumption with respect to the baseline. Three causes of energy variation were considered [41, 46]: i) change of energy services from 2015 to each milestone year; ii) improvement of the energy efficiency of the considered technologies from 2015 to each milestone year; and iii) commodity shifts among energy vectors (including the shift from other commodities to electricity).

Starting from the results of the developed scenarios in terms of energy consumption for the different commodities, the energy services associated to this scenario were calculated considering the evolution of the commodities energy efficiency in the milestone years (for each commodity, the average efficiency was calculated as the efficiency of the installed generation technologies weighted on their frequency in the different years). Based on these calculations, two ideal scenarios were developed: Business As Usual (BAU) and Increased Efficiency (IE), to be compared to the obtained results (identified as MODEL) [46]. MODEL results depend on the scenario considered from the previous analysis (e.g. BASE, TF, COMB1, etc.), depending on the analyst's choices.

BAU scenario was defined assuming null energy mix changes and null energy efficiency improvements of the single commodities technologies, with respect to 2015; by fixing the total energy services as in MODEL, the specific services of each commodity in 2030 and 2050 were re-distributed, keeping fixed their percentage distribution as in the baseline year. BAU energy consumptions were then calculated based on the so-defined energy services, associating to each commodity the energy efficiencies characteristics of the baseline year (dependent on RBs technologies). According to this calculation, the BAU scenario can represent the total final energy consumption of the building sector, assuming null incremental electrification and commodity shift and no technological improvement with respect to 2015.

Moreover, in order to consider the future technological improvements due to the increase of the efficiencies of the installed technologies, the IE scenario was built. Its energy consumptions were computed starting from the energy services of the BAU scenario, but considering the real improvement of energy efficiency of each commodity and milestone year, as projected by the scenario development. In this way, the IE scenario is able to tackle the future technological improvement achievable with respect to BAU scenario, even though it still does not consider any energy mix change or commodity shift (including the increasing electrification).

Finally, MODEL scenario (which results depend on the scenario analysis formerly described in this chapter) considers both technological improvement due to energy efficiency increase and commodity shifts, including electrification.

For each scenario, the total energy services in each milestone must be the same (Eq. 3.6), as well as the consumption of each commodity at the baseline year t_0.

$$S^t_{MODEL} = S^t_{BAU} = S^t_{IE} \tag{3.6}$$

In accordance with the definition of the three scenarios (BAU, IE and MODEL), it is possible to evaluate the contribution of the different influencing factors (i.e. energy efficiency, commodity shift, electrification) to the variation of the total final energy consumption. The TFC difference per each energy commodity between IE and BAU scenarios allows to estimate the contribution of energy efficiency to the overall variation (TFC^t_F) in each milestone year (Eq. 3.7), while the TFC difference between MODEL and IE scenarios allows to evaluate the contribution of the commodity shift (TFC^t_C) in each milestone year (Eq. 3.8), including the shift from other non-electrical commodities to electricity (e.g. due to the installation of heat pumps in substitution of existing fossil commodities).

$$TFC_F^t = TFC_{IE}^t - TFC_{BAU}^t \tag{3.7}$$

$$TFC_C^t = TFC_{MODEL}^t - TFC_{IE}^t \tag{3.8}$$

However, within the energy variation due to commodity shift (TFC_C^t), a quota is related to the commodity shift to other non-electrical technologies (e.g. the shift from oil or gas technologies towards biomass boilers). For this reason, it is important to isolate the contribution of electrification to the commodity shift ($TFC_{C,el,shift}^t$), in order to calculate the overall contribution of electrification to the TFC variation.

Considering the sole variation of energy consumption due to commodity shift (i.e. TFC variation between BASE and IE scenarios, TFC_C^t), per each energy commodity it is possible to evaluate two quota, as reported in Eq. 3.9 and 3.10:

$$TFC_{C,j}^{t,+} = TFC_{C,j}^t, if TFC_{C,j}^t > 0 \tag{3.9}$$

$$TFC_{C,j}^{t,-} = TFC_{C,j}^t, if TFC_{C,j}^t < 0 \tag{3.10}$$

Specifically, Eq. 3.9 represents the increase of energy consumption of the j_{th} commodity, while Eq. 3.10 represents the decrease of energy consumption of the j_{th} commodity, both due to commodity shift. In order to evaluate the contribution of electricity and non-electricity shifts to the decrease of non-electrical commodities consumption, Eq. 3.11 and 3.12 are used:

$$TFC_{C,el,shift}^t = -\left(\sum_j TFC_{C,j}^{t,-}\right) \cdot \frac{TFC_{C,el}^t}{TFC_{C,el}^t + \sum_j TFC_{C,j}^{t,+}} \tag{3.11}$$

$$TFC_{C,others,shift}^t = -\left(\sum_j TFC_{C,j}^{t,-}\right) \cdot \frac{\sum_j (TFC_{C,j}^{t,+})}{TFC_{C,el}^t + \sum_j TFC_{C,j}^{t,+}} \tag{3.12}$$

Eq. 3.11 allows to estimate the portion of non-electrical commodities decrease ($\sum_j TFC_{C,j}^{t,-}$) that is shifted to electricity, while Eq. 3.11 identifies the portion of non-electrical commodities decrease shifted to other non-electrical commodities (e.g. to biomass).

In the view of time, the energy consumptions variation with respect to the baseline year t_0 of each scenario can be assessed as follows, where Eq. 3.13 represents the overall variation of total final energy consumption according to the scenario analysis developed in this chapter.

$$\Delta TFC_{MODEL}^t = TFC_{MODEL}^t - TFC_{MODEL}^{t_0} \tag{3.13}$$

$$\Delta TFC_{BAU}^t = TFC_{BAU}^t - TFC_{BAU}^{t_0} \tag{3.14}$$

$$\Delta TFC^t_{IE} = TFC^t_{IE} - TFC^{t_0}_{IE} \tag{3.15}$$

Moreover, the energy variations due to the different influencing factors can be assessed as in Eq. 3.16 and 3.17, in relation to energy efficiency and commodity shifts, respectively.

$$\Delta TFC^t_F = \Delta TFC^t_{IE} - \Delta TFC^t_{BAU} \tag{3.16}$$

$$\Delta TFC^t_C = \Delta TFC^t_{MODEL} - \Delta TFC^t_{IE} \tag{3.17}$$

In order to isolate the electricity replacement occurring in ΔTFC^t_C, the percentage contribution of electricity shifts can be computed starting from Eq. 3.11 and 3.12:

$$\%_{el,shift} = \frac{TFC^t_{C,el,shift}}{TFC^t_{C,el,shift} + TFC^t_{C,others,shift}} \tag{3.18}$$

Eq. 3.19 reports the commodity shift to electricity, computed based on Eq. 3.17 and 3.18:

$$\Delta TFC^t_{C,el,shift} = \Delta TFC^t_C * \%_{el,shift} \tag{3.19}$$

In order to assess the overall contribution of electrification to the final energy consumption variation, the different contributions of the influencing factors in terms of electricity consumption changes must be considered. The numerator $N^{t,-}$ of the indicator estimating the contribution of electrification is composed by three terms (the "-" indicates the sign of the variation):

- the electricity consumption variation due to service change is considered ($\Delta TFC^{t,-}_{BAU,el}$), in case BAU scenario provokes a negative variation of the total final energy consumption;
- the electricity consumption reduction due to efficiency variation with respect to BAU scenario is considered ($\Delta TFC^{t,-}_{F,el}$);
- the electricity consumption variation due to commodity shift to electricity with respect to IE scenario is considered ($\Delta TFC^{t,-}_{C,el,shift}$).

The denominator D^t, instead, does not consider the sole variation of the final energy consumption (as assessed in Eq. 3.13). Indeed, in case both the ideal scenarios BAU and IE induce negative variations of the total final energy consumption, the denominator is calculated simply as in Eq. 3.20, which represents the overall TFC variation projected in the MODEL scenario.

$$D^{t,-} = \Delta TFC^{t,-}_{BAU} + \Delta TFC^{t,-}_F + \Delta TFC^{t,-}_C \tag{3.20}$$

Otherwise, in case at least one of the two scenarios provokes positive variations of final energy consumption, the absolute value of the denominator should account the higher variations occurring when passing from one scenario to another. For the TFC variation, in 2030, the BAU scenario results in an increment of the final energy consumption with respect to the baseline year; in this case, the variation due to energy efficiency improvement is higher than in the previous case, since it should compensate also the TFC increase of the BAU scenario. For this case, therefore, the denominator of the electrification contribution is calculated as in 3.21.

$$D^{t,-} = \Delta TFC_{F}^{t,-} + \Delta TFC_{C}^{t,-} \tag{3.21}$$

Therefore, in conclusion, the contribution of electrification (EC^t) to the overall final energy consumption at time t is computed as in Eq. 3.22:

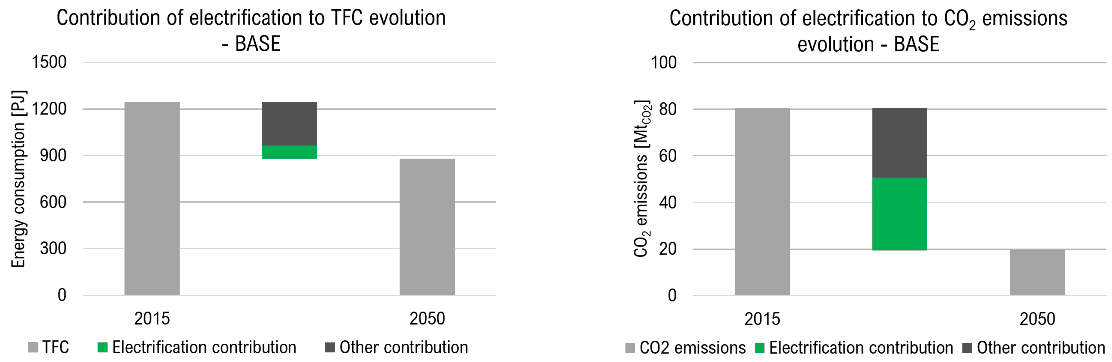
$$EC^t = \frac{N^{t,-}}{D^{t,-}} = \frac{\Delta TFC_{BAU,el}^{t,-} + \Delta TFC_{F,el}^{t,-} + \Delta TFC_{C,el}^{t,-}}{\Delta TFC_{BAU}^{t,-} + \Delta TFC_{F}^{t,-} + \Delta TFC_{C}^{t,-}} \tag{3.22}$$

The numerical model so far described can be used to estimate the contribution of electrification to other KPIs (i.e. CO_2 emissions, per capita TFC, energy intensity, etc.), by using appropriate multiplication factors (e.g. CO_2 emission factor, population and GDP estimates, etc.) [46].

Key findings and discussion

In the followings, some key findings deriving from the application of this approach to the developed scenarios are presented, firstly considering the results obtained for the BASE scenario. Figure 3.24 shows the evolution from 2015 to 2050 of final energy consumption and CO_2 emissions, highlighting the contribution of electrification to the KPIs variation. The term "other contribution" is intended to cover all the combined effects that can influence the KPIs variation (e.g. energy efficiency improvement, technological shift to other non-electric carriers, service changes, etc.).

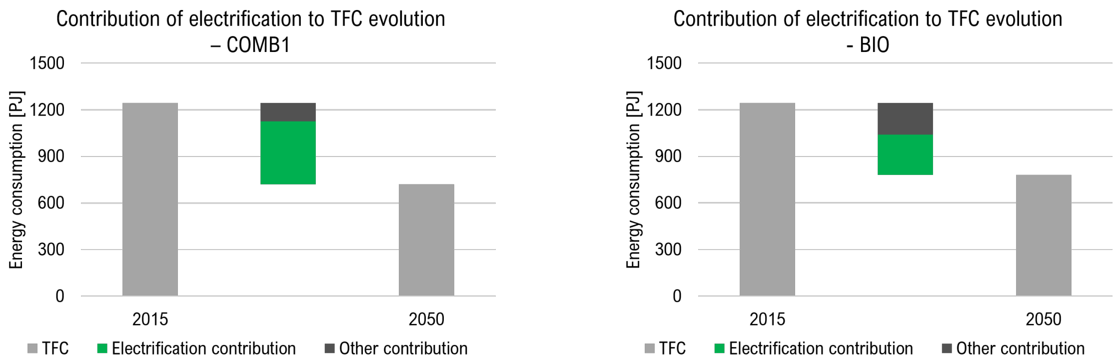
The definition of BAU and IE cases allows to identify specific theoretical pathways, not including any efficiency improvements or technological shifts (including the electrification of final uses). In particular, by considering the sole IE condition and, thus, by excluding the possibility of technological shifts, the TFC reduction in 2050 would be equal to 9%, instead of the obtained 29%, while according to BAU scenario (null efficiency improvements and technological shifts), the sector would undergo a 3.6% increase of energy consumption from 2015 to 2030, and a subsequent 4.2% reduction from 2030 to 2050, showing an almost null variation with respect to the baseline. Focusing on the complete BASE scenario, instead, thanks to the diffusion of more efficient technological options (mainly heat pumps), the average energy efficiency (obtained weighting the individual efficiencies) increased of 10.6% and 40.8% in 2030 and 2050 (with respect to 2015), with electrification playing a crucial role especially in the 2030-2050 period.



(a) Energy consumption (b) CO_2 emissions

Figure 3.24: Electrification contribution to (a) TFC and (b) CO_2 emissions variations up to 2050 for the overall residential sector for BASE scenario.

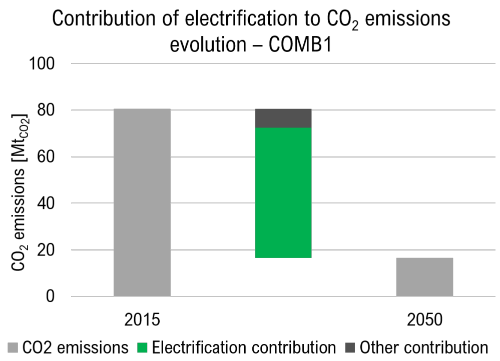
Two additional scenarios were selected, among the ones previously discussed in section 3.1.5, to be compared to the BASE case: i) COMB1 scenario, which represented the policy scenario inducing the highest energy consumption reduction and electrification share (developed combining TF and INC scenarios); and ii) BIO scenario, which considered the sensitivity on the biomass price. TFC and CO_2 emissions evolutions are reported in Figure 3.25 and Figure 3.26, respectively.



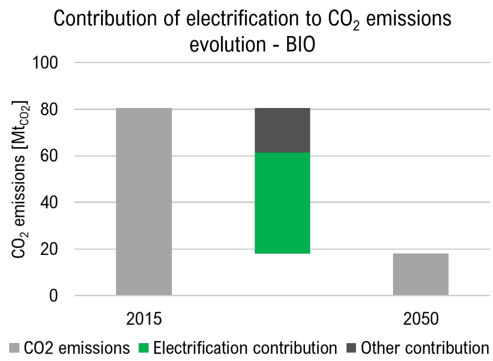
(a) COMB1 scenario (b) BIO scenario

Figure 3.25: Electrification contribution to TFC variation up to 2050 for the overall residential sector for (a) COMB1 and (b) BIO scenarios.

The highest electrification contribution to either TFC or CO_2 emissions variation is achieved by COMB1 scenario, while BIO represents an intermediate situation between COMB1 and BASE conditions. Surely, both COMB1 and BIO scenarios experience a stronger diffusion of electric technologies, compared to BASE scenario, thus achieving higher consumption reductions and electrification shares. However,



(a) COMB1 scenario



(b) BIO scenario

Figure 3.26: Electrification contribution to CO_2 emissions variation up to 2050 for the overall residential sector for (a) COMB1 and (b) BIO scenarios.

even though the increment of the biomass energy price advantages heat pumps over biomass boilers already in 2030, in BIO scenario still biomass boilers are competitive in some RBs, thus increasing their share in the building stock; conversely, COMB1 scenario strongly advantages electric technologies, reducing the diffusion of biomass boilers (in both thermal uses), and thus resulting in larger benefits associated to the higher electrification of the sector.

To conclude, Table 3.5 summarizes the main KPIs computed for the three scenarios (BASE, COMB1 and BIO), while Table 3.6 shows the electrification contribution to the variation of the most relevant KPIs, assessed according to the presented approach. To support the multi-dimensionality of the transition process, as well as to highlight how the renovation of the building stock can provide multiple benefits (not only energy-related), the considered KPIs belong to three main dimensions (i.e. energy, environmental, socio-economic spheres), emphasizing how an electrification roadmap for the entire residential stock may affect also non-energy domains.

3.1.7 Conclusions and further investigation

Due to its significant energy and environmental impact, the building sector is acknowledged as a major player in the next energy transition. Electrification has been widely recognized as a possible pathway towards the decarbonization of the sector, especially if coupled with the evolution of electricity generation towards a climate-neutral mix. The role of electricity in the transition of the building sector was already discussed in Chapter 2, focusing on a micro perspective (i.e. single technology, individual building) and on the benefits associated to electric technologies for heating and cooling purposes. Specifically, the previous application on Italian individual RBs has led to the development of a multi-dimensional aggregate

Table 3.5: Multi-dimensional KPIs: comparison between BASE, BIO and COMB1 scenarios.

		BASE		**BIO**		**COMB1**	
KPI	**2015**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
TFC [PJ]	1242.9	1163.9	878.4	1048.9	779.5	980.4	721.3
% TFC variation (w.r.t 2015)	-	-6%	-29%	-16%	-37%	-21%	-42%
Per capita TFC [GJ/pers]	20.9	20.0	15.9	18.1	14.1	16.9	13.1
% per capita TFC variation (w.r.t 2015)	-	-4%	-24%	-14%	-32%	-19%	-37%
CO_2 emissions [Mt]	80.5	41.0	19.4	39.9	18.1	38.3	16.6
% CO_2 emissions variation (w.r.t 2015)	-	-49%	-76%	-50%	-78%	-52%	-79%
PM emissions [kt]	87.0	69.7	59.7	50.8	43.5	66.8	57.2
% PM emissions variation (w.r.t 2015)	-	-20%	-31%	-42%	-50%	-23%	-34%
Energy intensity [GJ/M€]	1025.8	732.2	460.0	699.0	439.7	683.9	430.4
% energy intensity variation (w.r.t 2015)	-	-29%	-55%	-32%	-57%	-33%	-58%
Carbon intensity [kt/G€]	51.7	19.5	6.6	19.0	6.2	18.2	5.6
% carbon intensity variation (w.r.t 2015)	-	-62%	-87%	-63%	-88%	-65%	-89%

Table 3.6: Electrification contribution to the relevant KPIs: comparison between BASE, BIO and COMB1 scenarios.

	BASE		**BIO**		**COMB1**	
Electrification contribution to:	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
% TFC variation	14%	23%	36%	56%	75%	78%
% per capita TFC variation	14%	30%	36%	63%	75%	87%
% CO_2 emissions variation	63%	51%	76%	70%	89%	87%
% PM emissions variation	0%	0%	0%	0%	45%	47%
% energy intensity variation	32%	32%	35%	37%	40%	39%
% carbon intensity variation	50%	41%	58%	49%	66%	58%

indicator (i.e. GCES) able to express the reciprocal competitiveness of diverse technological options, to be used in support of policy strategies definition and energy planning. In other words, GCES was defined as an analytical tool in the hand of decision-makers for policy-oriented purposes, rather than as an indicator able to express and drive consumers' choices in case of retrofit. This objective, instead, was the main motivator of this section.

In the attempt of translating the environmental benefits of the alternative technological solutions into financial terms, the application aimed to simulate an hypothetical scenario in which environmental performances would be able to influence consumers' choices in case of retrofit. The study aimed to perform a technological-oriented scenario analysis, to disclose information on the potential of electrification of the thermal uses in the Italian residential stock, and to inform on the contribution of electrification to the future energy consumptions and emissions reductions, through the use of appropriate multi-dimensional KPIs. This section assessed the role of electricity according to a meso scale standpoint (national scale), which is of interest for the definition of long-term strategies of decarbonization and energy efficiency improvement for the building sector.

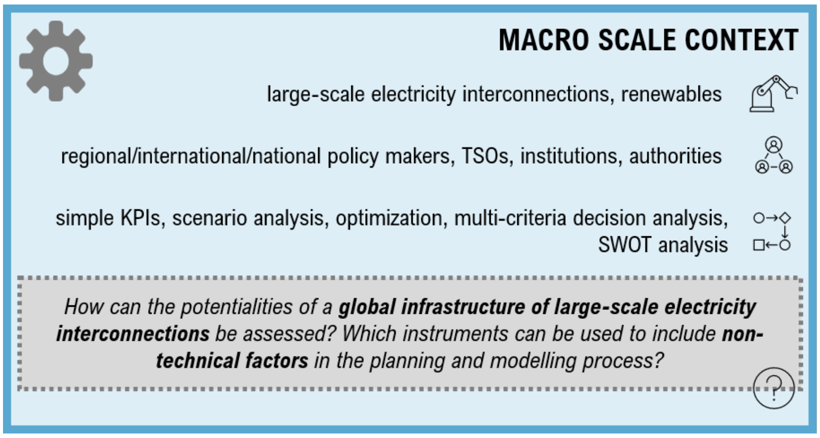
Extending the analysis reported in Chapter 2, this application allowed to pinpoint the most significant drivers and the main policy-based challenges towards the sector electrification, taking into account the potential for electric technologies to be competitive in the residential sector in future years. In particular, the analysis attempted to stress how the quantification of the environmental benefits guaranteed by low-carbon solutions (including heat pumps) could further push consumers towards their adoption. In line with this, on the basis of the newly-developed GCCA aggregate indicator, the application allowed to compare and rank the renovation strategies (i.e. technologies for heating purposes) in relation to the environmental benefits they can guarantee with respect to the impact of the original building systems. By definition, for each RB, the most competitive alternative technology was assumed as the one characterized by the lowest indicator, meaning that its global cost is reduced by its high capability of decreasing the original emissions. According to this, the GCCA-based model assumed that, in case of retrofit, consumers are willing to choose the technology characterized by the lowest indicator. Even though the GCCA definition allowed to rank the technologies considering their multi-dimensional performance (both financial and environmental), the GCCA-based likelihood of technological shift simulated an hypothetical (even though probable) scenario, in which future policy actions will be based on the carbon intensity of the technological solutions at disposal, and thus will push private decisions towards the adoption of low-carbon technologies.

According to the GCCA-based scenario analyses, electric technologies still have competitors, like generation systems fuelled by biomass, unless one of the two solutions is advantaged by energy prices, as happens in 2050 in favour of heat pumps. Diverse policy strategies were compared to test their effectiveness in boosting the electrification of the sector. Existing incentive mechanisms are not benefiting heat pumps enough yet, promoting biomass and electricity competition (INCR scenario). In particular, the analyses conducted starting from the baseline scenario (BASE) have raised some issues: a review and stabilisation of existing incentive mechanisms may enhance the future electrification of buildings (INC scenario); moreover, the spread of electric technologies could be pushed by fees and new regulation models, properly introduced by service providers, policy makers and authorities. In this regard, the analysis have highlighted the role that environmental taxes can have in the sector transition, since, even though both electric and biomass-fuelled options are targeted as low-carbon, biomass technologies are penalized by their bad performance in terms of local air pollution, being the largest PM emitters among the considered technologies.

Despite the interesting results coming from the developed medium- and long-term scenario analyses, the work has some limitations, which open the way to future development, as partly discussed in section 2.2. Firstly, as already mentioned in the previous section, only three technological options were assumed as eligible for retrofit, and, for this reason, future work should be undertaken in order to include other technologies in the model. In line with this, the adoption of renewable solutions (e.g. PV panels, solar thermal collectors, etc.) should be considered as well, in order to push the sector towards its transformation into a zero-energy or zero-carbon one. Moreover, the analysis had thermal uses as main targets, being currently the least electrified final uses in Italian residential buildings. However, due to the increasing demand for air conditioning, as a consequence of climate change, a more detailed analysis of the penetration of space cooling technologies should be developed, also to highlight the benefits offered by heat pump solutions, which can provide both services with a single reversible unit (conversely from gas or biomass options, which should be coupled with electric technologies for cooling purposes). Similar analyses could be performed for non residential buildings, even though the sector is more highly fragmented than the residential one and, thus, less characterizable in terms of archetypes. Finally, even though the competitiveness of electric technologies is linked to all the policy-based issues discussed in the study, a demand reduction strategy for the residential sector should also be assessed and set, in order to boost even further the sector transition towards electrification. Therefore, future considerations will be devoted to couple the technological-oriented study here described with the possible interventions able to reduce the energy needs of buildings (e.g. envelope insulation, windows replacement, etc.), as well as the thermal losses of emission and distribution sub-systems, which were not the target of the performed scenario analyses.

Chapter 4

Macro scale context



Moving from demand-side transformations (mostly related to the issue of end uses electrification, in relation to the building sector, albeit at different scales) to supply-side considerations, this chapter focuses on the macro scale, aiming to simulate medium- and long-term scenarios of a RES-based energy paradigm based on the Global Energy Interconnection (GEI) vision, exploring the associated challenge of transmission expansion planning at global and European scale. The chapter is focused on the development of typical techno-economic power system models at different spatial scales and on the use of multi-dimensional KPIs and evaluation tools as inputs to traditional modelling exercises.

This chapter is divided in two parts, each describing a specific application at macro scale. The first part ("Energy scenario analysis at global scale") is concentrated on a global scale application, which allows to simulate a preliminary global grid under the premises of the GEI vision and a globally integrated electricity market, developing an optimal power flow analysis to investigate the highest demanding conditions and to estimate the capacity of the interconnections needed to accommodate this vision. The optimization approach is developed performing a comparative analysis among diverse scenario assumptions, in order to investigate the effects that different climate mitigation policies could have on the evolution of electricity consumption and generation in different world regions. This study, despite the encountered limitations, highlights the necessity to change the focus from a purely techno-economic modelling to a multi-layered framework, needed when dealing with energy transition issues.

Therefore, the second part ("Multi-dimensional energy planning at European scale") is devoted to the study and use of proper multi-dimensional decision-making tools for supporting energy planning strategies and, mainly, the transmission expansion planning process. A hybrid multi-criteria methodology (i.e. hybrid A'WOT method) is applied in order to identify the main actors, criteria, interests and concerns related to the development of interconnection corridors between Europe and its surrounding areas, allowing to rank the European countries most eligible for hosting these interconnections from a multi-dimensional standpoint. In order to test and explore the possibility of integrating multi-criteria decision analysis with traditional power system modelling, the outcomes of the application of the A'WOT method are used as input to an optimization approach, aiming to investigate the capability of future European expansion plans in accommodating the power flows forecasted by the GEI vision, showing possible bottlenecks for its realization.

4.1 Energy scenario analysis at global scale

4.1.1 Overview

To strive towards the long-term objective of emissions reduction, actions to increase energy systems decarbonization are becoming urgent. The higher integration of renewable energy sources and the greater electrification of end uses are the basis of the GEI vision, which is built around the concept of RES deployment in energy-rich but remote areas (i.e. Equatorial and Arctic regions for solar and wind power, respectively) and of the use of UHV power lines, mainly DC, to redistribute this clean energy to the major load centres. In this context, long-distance transmission grid improvements are fundamental to integrate higher RES levels and to increase the network flexibility and reliability. The modelling of GEI is of great importance, in order to evaluate and simulate the feasibility of such system. This section introduces the GEI concept from a global perspective, aiming to model a preliminary globally interconnected power network. Starting from a baseline condition, six scenarios are developed to forecast diverse electricity generation and consumption trends in 2030 and 2050. Optimal power flow is used for simulating a typical winter day, with an hourly time-step, assuming an ideal condition of global electricity market and null transmission constraints. A set of multi-dimensional regional- and global-scale KPIs (i.e. technical, socio-economic and environmental) is used to compare the proposed scenarios and to quantitatively assess the possible benefits and concerns behind the realization of a GEI-based paradigm.

Keywords Global Energy Interconnection, long-term scenarios, optimal power flow, globally interconnected electrical network, global electricity market.

Declaration The topics described in this chapter were previously published in the following publications:

- **G. Crespi**, T. Huang, Z. Han, E. Bompard, S.P. Corgnati, *A simplified electrical network model for techno-economic analysis of globally integrated electricity market*, Proceedings of Energy for Sustainability Conference 2019: Designing a Sustainable Future, 24-26 July 2019 [176].

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4.1.2 Background

The realization of a GEI-based energy scenario will surely involve a structural modification of global energy systems, affecting the entire energy chain, from production (due to the intensive RES penetration), to import, from transformation to end-use (because of the higher level of electrification) [32].

As previously mentioned, grid improvements are fundamental to integrate higher renewable levels and to increase the network flexibility and reliability [88]. In this context, the modelling of GEI is of great importance, aiming to assess the feasibility of such system; moreover, in order to better tackle both benefits and obstacles of such global energy infrastructure, large-scale energy models are usually used as the basis for broader strategic energy planning [177]. The same consideration is valid for the power sector, which evolution towards a renewable system should be studied, not only in techno-economic terms, as usually implemented in power system analysis, but also considering the possible environmental, social, political implications that its transformation can bring. If the techno-economic assessment of individual interconnections between different world regions is more present in literature, few global grid models have been developed and discussed [75]. Brinkerink et al. reported a review of global scale assessments, highlighting also the main limitations of the literature works [75]. Moreover, in Ref. [79], some cases of global scale models were presented. An example of global grid concept is presented in Ref. [71], highlighting the role of HVDC systems for its realization and the opportunities behind it. Brinkerink et al. reported their first steps towards the realization of a global model, describing the development of an intermediate model of interconnection between Europe and North America [178]. A 30-nodes model for the European network (EU28 plus Norway and Switzerland) was connected to a North-American model (with 20 nodes for United States and 8 nodes for Canada), by means of intercontinental UHV interconnections [178]. The analysis has shown that, thanks to the presence of different time zones, the demand peaks in the two main consumption areas (Europe and North America) occurred in different moments, and that, in many cases, peaks in Europe where counterbalanced by off-peaks in North America and vice versa [178]. The model, simulated over an entire year, explored how the flow is directed towards Europe, due probably to the least-cost generation in North America [178]. In their work, authors described the main challenges behind the realization and simulation of global scale models, among which data availability is perceived as a major obstacle [178]. Indeed, open access data are not always present, and, in some cases, transmission system operators (TSOs) have no interest in sharing their data [178]. Therefore, as reported in Ref. [79], "to partly overcome this difficulty, a common approach implemented for such simulations is to use existing generation and demand profiles of similar regions (e.g. in terms of population, GDP, electricity generation portfolio, etc.) and to scale them according to time zone, electricity demand, and peak values [178]".

Since power systems play a crucial role in the achievement of the decarbonization strategies, their modelling is needed in order to perform forecasting analyses. Long-term scenarios are in demand to evaluate the effects of energy policies for reducing the environmental impact of current systems. As pointed in Ref. [26], diverse forecasting scenario analyses have been developed in literature. However, few impact assessment studies were performed at global scale, often focusing on a single country or a group of countries (i.e. European Union) [26]. Long-term forecasting scenarios are usually evaluated by defining a set of energy- or socio-economic-related metrics, aiming to highlight the traced pathways and to compare them with international or national decarbonization targets.

In line with the above, and focusing on the GEI vision, this section aims to develop a simplified global electricity network, to simulate the presence of large-scale and long-distance interconnections according to different electricity generation and demand hypotheses, in the assumption of the existence of a global electricity market. The simulations are performed on the basis of electricity generation and consumption profiles determined based on existing scenarios developed by the World Energy Outlook (WEO) and on a newly-developed scenario, built starting from GEI projections [32]. Optimal power flow analysis is performed, aiming to study the capacities of the identified power corridors needed to deal with this complex system. In order to take into account the environmental and socio-economic aspects potentially related to these ideal scenarios, the developed models are compared in terms of specific region- and global-based KPIs.

4.1.3 Methodology

The methodology is structured around the following main steps, as summarized in Figure 4.1:

- **study: global grid modelling**. A preliminary global grid modelling is developed, once identified the energy and economic parameters to be used as input for the simulations. Based on literature-based scenarios, electricity generation and consumption information are gathered to model diverse scenarios for a medium- (2030) and long-term (2050) time horizon.

- **simulate: optimization**. Optimal power flow analysis is performed, aiming to estimate the needed interconnection capacities, for the baseline condition and for the different scenarios for 2030 and 2050. Optimization is run for the highest demanding condition (i.e. winter peak load day), with an hourly time-step.

- **synthesize and support: definition and computation of relevant KPIs**. Different regional- and global-scale KPIs are defined, belonging to technical, socio-economic and environmental dimensions, to compare the results obtained from the developed scenario analysis.

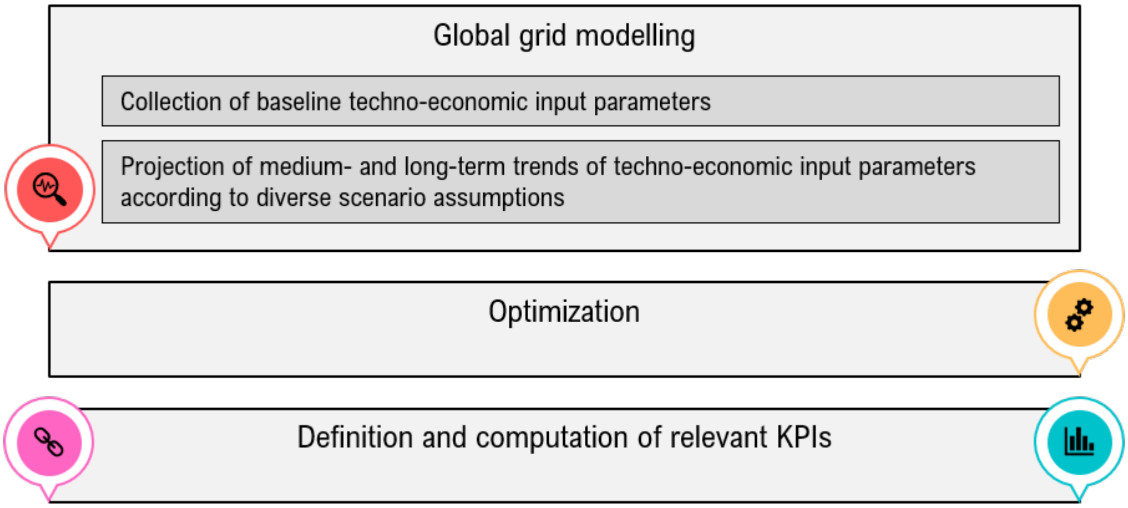

Figure 4.1: Main methodological steps.

Study: global grid modelling

A primary focus of the application is the modelling and simulation of an interconnected global electrical network, performing a techno-economic analysis of possible scenarios of electricity interconnections, in a global market vision. To do this, a simplified global network model was built, dividing the world into a significant set of regions. Each world region was designed as an equivalent bus, for which a set of generators was defined, considering the different sources locally available for electricity production. Each type of generation technology was modelled as a single generator with equivalent capacity and connected to the bus. Moreover, normalized hourly load profiles and peak loads were gathered for the considered zones.

For each area, cost information are needed. In particular, the Levelized Cost of Electricity (LCOE) was selected as economic indicator, allowing to compare the costs of a single unit of electricity produced by different power generation plants over their lifetime. This method has been widely used in modelling and policy discussions [179]. LCOE is calculated based on "the equivalence of the present value of the sum of discounted revenues and the present value of the sum of discounted costs" [179]. This equivalence is based on the assumption that both the real discount rate and the electricity tariff are stable and do not vary during the lifetime of the project under consideration [179]. LCOE represents the cost that, if assigned to each unit of energy produced by the system over the entire period of analysis (lifetime), equals the total life-cycle cost (TLCC), when discounted back to the base year [179]. LCOE can be calculated as in Eq. 4.1:

$$LCOE = \frac{TLCC}{\sum_{k=1}^{N} \frac{E(k)}{(1+d)^k}} \tag{4.1}$$

where N represents the total number of k_{th} periods (years), $E(k)$ is the quantity of energy produced during the k_{th} year, d is the discount rate and TLCC represents the total life-cycle cost, defined as in Eq. 4.2:

$$TLCC = \sum_{k=0}^{N} \frac{C(k)}{(1+d)^k} \tag{4.2}$$

where $C(k)$ represents the general voice of cost incurred in the k_{th} period, including investment costs (at the period $k = 0$), annual operation and maintenance costs (both fixed and variable), carbon and decommissioning costs [179].

In this application, each generator was associated to a LCOE value, defined for the different world regions, in light of national generation mixes, technology maturity and operational costs. Despite the limitations that this approach might have, LCOE was selected in the sake of comparing alternative technological options (or sources) for electricity generation.

Furthermore, the application aimed to evaluate the effects that different climate policies and decarbonization targets could have on the global grid model. Therefore, different scenarios for 2030 and 2050 were developed, to project the needed interconnection capacities according to different conditions of electricity generation mix, electricity consumptions and costs based on literature findings. Moreover, based on GEI assumptions in terms of RES installations in Equatorial and Arctic regions and electricity demands growths, a GEI-based scenario was developed [32].

Simulate: optimization

The global grid model was tested using the Optimal Power Flow (OPF) approach, which provides the ability to optimally dispatch electricity generation in an area or group of areas, determining the optimal output of a set of electricity generation facilities to meet the load at the lowest possible costs [180]. The analysis allowed to define the optimal power flows between the different world regions, evaluating the system capability to adequately supply the connected loads in a cost-effective way (i.e. at the lowest cost per MWh delivered). The general optimization problem can be written as in Eq. 4.3:

$$\begin{aligned} &min f(x) \\ &s.t. h(x) = 0 \\ &g(x) \geq 0 \end{aligned} \tag{4.3}$$

where x is the decision variable, containing the generation output of each type of generator and the load for each equivalent bus; $f(x)$ is the total cost of electricity bought from the global electricity market; $h(x)$ is the global power balance; and $g(x)$ represents the operational constraints, including the capacity limits of each type of generator.

Synthesize and support: definition and computation of relevant KPIs

The comparison and assessment of the simulated scenarios was based on a set of KPIs, belonging to three main dimensions: energy-technical, socio-economic and environmental (as reported in Table 4.1).

Table 4.1: Definition of relevant regional- and global-based KPIs.

Dimension	Indicator	Unit	Spatial scale	Source
Energy/Technical	Total electricity generation	TWh	World	-
	Total electricity consumption	TWh	World	-
	Maximum interconnection capacity	GW	Power corridor	-
Socio-economic	Net Electricity Trading (NET)	M$	World region	Eq. 4.4
	Cost of generating electricity (C_g^w)	M$	World region	Eq. 4.5
Environmental	Total GHG emissions	Mt	World	-

According to the energy-technical perspective, it was possible to estimate the total electricity generation and consumption over the 24 hours of simulation, as well as to evaluate the highest needed interconnection capacities, for the different scenarios. Furthermore, the net electricity trading (NET) and the cost of generating electricity were defined as socio-economic indicators. In detail, the NET indicator was designed to economically express the electricity trading of the different geographical zones. In particular, it was defined as in Eq. 4.4:

$$NET(i) = \sum_{t=1}^{24} (G(i,t) - C(i,t)) \cdot LMP(t) \tag{4.4}$$

where t is the hourly time-step, $G(i,t)$ is the electricity generation of the i_{th} world region at the t_{th} time-step, $C(i)$ is the electricity consumption of the i_{th} world region at the t_{th} time-step and $LMP(t)$ is the marginal price of the global market at the t_{th} time-step. The calculation assumed the presence of a global electricity market, in which LMP is equal in all buses in each hourly time-step. The net electricity indicator aimed to differentiate the importing and exporting countries, for the winter peak load day, for each scenario, to verify possible changes in the behaviour of the regions, in accordance with the different policy assumptions.

With the same parameters, from a purely financial standpoint, the cost of generating electricity was calculated for the different scenarios and world regions, according to Eq. 4.5:

$$C_g^w(i) = \sum_{t=1}^{24} C(i,t) \cdot LMP(t) \tag{4.5}$$

Finally, to study the global interconnection framework also from the environmental standpoint, global GHG emissions from electricity production for the peak load day were calculated for each scenario, in terms of CO_{2eq} emissions generated by combustible fuel usage for generating electricity.

4.1.4 Case study

Global grid modelling and optimization

The simplified global network model was built by firstly identifying the 15 world regions reported in Table 4.2. PowerWorld Simulator tool was used for modelling and simulating the global grid [180].

Table 4.2: Considered geographical areas.

Geographical area	**Code**
European Union	EU
Non-EU countries	NEU
Eastern Europe and Eurasia	EEE
Russian Federation	RUS
North America	NAC
Brazil	BRA
Latin America and Caribbean (excluding Brazil)	LCN
Middle East	MEA
India	IND
Japan	JPN
China	CHN
Eastern Asia	EAS
Other Asian countries	OAS
Oceania	OCN
Africa	AFR

Through OPF analysis, the model allowed to compute generation dispatch and power flows, performing a preliminary top-level infrastructure planning; for this reason, the highest demanding conditions were used to size the corridors. The simulation was performed selecting the winter peak (for the Northern hemisphere) as the highest load condition (being the assumption valid for the European continent, which will be the focus of the following section 4.2), with an hourly time-step, for assessing the hourly variation of power flow quantities due to changes in load, generation, transmission line status.

Each world region was designed as an equivalent bus, for which a set of generators was defined, considering the different sources locally available for electricity production: coal, natural gas, oil products, bioenergy (considering biomass and biofuels), nuclear, hydro, wind, solar, geothermal and marine (i.e. tide, waves, etc.) sources. Due to data availability, the combustible fuels of each region were combined into a single generator, named "Combustible fuels". Each type of generation technology was modelled as a single generator with equivalent capacity and connected to the bus. Maximum generation data in MW were derived from statistical sources [181, 182]. Specifically, each node was characterized by hourly generation profiles for PV and wind sources and by aggregated generation capacities for the other commodities, considering their availability and capacity factors and keeping them constant for the 24 hours of simulation. Load data were accounted in terms of normalized power profiles and of winter peak load values for the different world regions, set accordingly to time zones, using the Coordinated Universal Time (UTC) standard as reference, assuming a single time zone per each world region. In this way, time and seasonal differences were taken into account. Finally, prices were set according to capital (CAPEX) and operating expenditure (OPEX); specifically, the generation cost curve was set accordingly to the LCOEs of each geographical area. For this analysis, the considered LCOE values were obtained from Refs. [179, 183, 184, 185, 186].

The model consisted of a total of 19 nodes, 15 of which identified by the considered world regions. Four additional nodes were included in the model in order to consider the installations of wind power in the Arctic region, according to Ref. [32], as will be later discussed. A total of 27 HVDC transmission corridors interconnected the 19 nodes, forming the backbones of GEI. The analysis was not designed to study the internal connections within each region, but to investigate their optimal interconnections. To this purpose, Liu's assumptions [32], coupled with the recent works developed by the Global Energy Interconnection Development and Cooperation Organization (GEIDCO), were used as reference in order to hypothesize the possible connections of transmission lines. Figure 4.2 and Figure 4.3 show the transmission lines inserted in the model. For this modelling exercise, the following assumptions were done: i) presence of a global electricity market; ii) needed interconnection infrastructure already in place to support such global trading; iii) only DC model used; iv) no transmission line limit set, due to data unavailability; v) identical parameters for all lines; vi) inelastic load in each bus. No detailed analysis on the location of buses or interconnection corridors was performed, due to lack of data. However, assuming the average length of the power corridors of approximately 2000 - 5000 km, no AC lines were included in the model.

Coherently with these assumptions and mainly based on the hypothesis of the presence of an effective global electricity market, a baseline scenario for 2014 was built [176], fully characterized based on statistical data from IEA [181] and UN statistics [182], used as the basis for the scenarios building. Particularly, data on

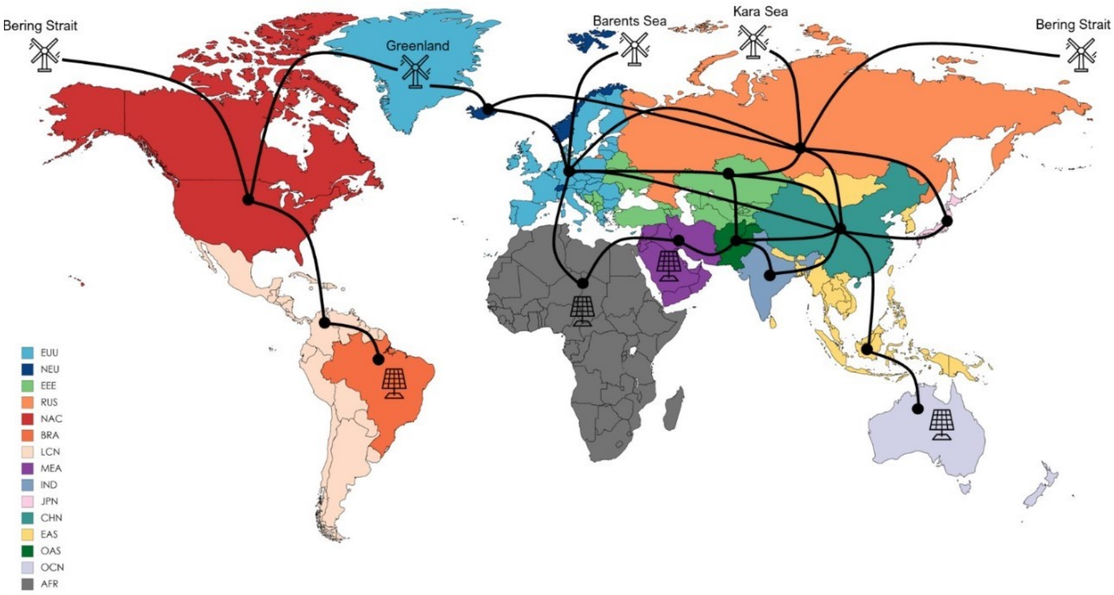

Figure 4.2: Simplified 19 nodes global grid model and identification of the 15 world regions.

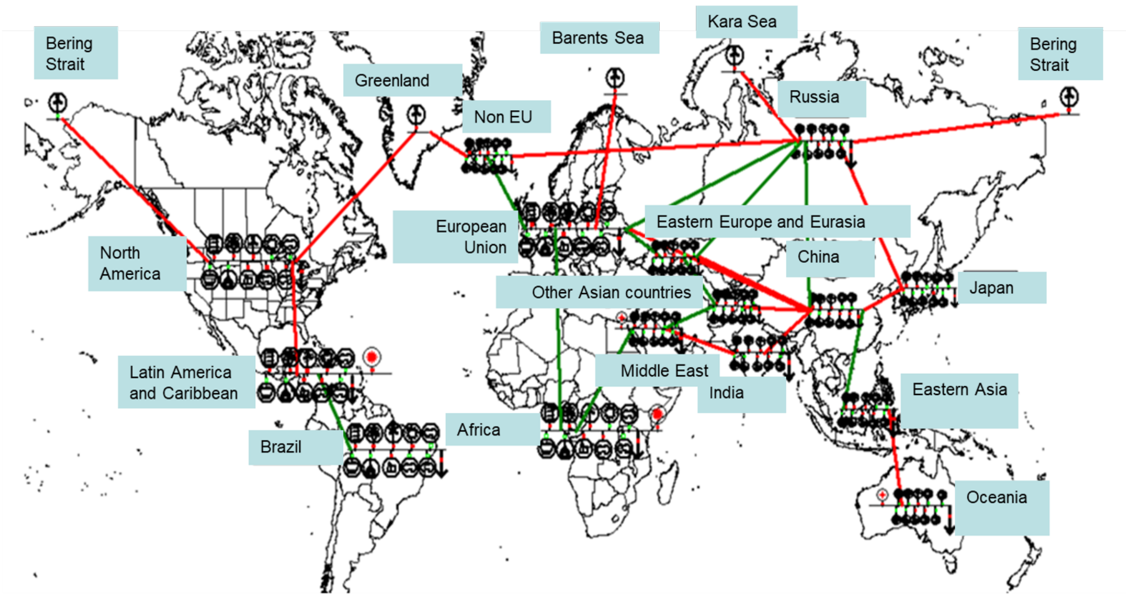

Figure 4.3: Model of the simplified 19 nodes global grid model and identification of the 15 world regions on PowerWorld software.

installed capacity and electricity generation by commodity, typical load profiles and peak loads were collected for 2014, and clustered in accordance with the assumed geographical sub-division.

Scenarios definition

To estimate the capacities of the needed interconnection corridors in a medium- and long-term time horizon, different trends of electricity generation and consumption were defined, projecting the baseline electricity data up to 2030 and 2050. Starting from the review developed by Bompard et al. [26], three scenarios were selected and, based on their assumptions, three specific power models were developed per each time horizon: Business as Usual (BAU), Real Policy (REP) and Global Energy Interconnection (GEI).

Business as Usual (BAU) scenario This scenario was built as a benchmark useful for measuring the impact of different policies (mainly descriptive of environmental targets) on electricity trends. For its building, the IEA "Current Policy" scenario was selected as starting point [181], considering its projections of electricity generation data up to 2050. In terms of peak load values, the growth rates of electricity generation were used to project the baseline winter peak loads in 2030 and 2050. As for LCOEs, costs for combustible fuels, geothermal, nuclear were maintained equal to 2014 values; for the renewables (i.e. hydro, solar, wind), the initial LCOEs for 2014 were reduced by 18% and 23% for 2030 and 2050, respectively [187].

Real Policy (REP) scenario This scenario aimed to represent a more "realistic" trend, considering a reasonable set of policies (including COP21 and Nationally Determined Contributions targets) that would be implemented during the considered time horizon. The IEA "New Policy" scenario was chosen as starting point [181], according to which assumptions the input data for the OPF analysis were projected for 2030 and 2050. LCOEs for combustible fuels were increased by 10% in all world regions with respect to 2014 values, assuming the adoption of carbon pricing mechanisms on combustible fuels, to boost the achievement of environmental targets. LCOEs for geothermal, nuclear and other sources were maintained equal to 2014 values, while for the renewables (i.e. hydro, solar and wind), the initial LCOEs for 2014 were reduced of 28% and 33% for 2030 and 2050, respectively.

Global Energy Interconnection (GEI) scenario This scenario represented an "extreme" implementation of the electricity triangle concept. It was defined based on Ref. [32], extrapolating information in terms of RES-based electricity generation and installed capacity in Arctic and Equatorial regions, as well as in terms of regional demand growth projections up to 2050. According to Ref. [32], wind installations were placed in Bering Strait, Greenland, Barents Sea and Kara Sea, while solar PV generators were added in Africa, Latin America, Oceania and Middle East existing buses. The values of installed capacities, extracted from Ref.

[32], are reported in Table 4.3. For all the other geographical zones, the scenario was built based on BAU assumptions in terms of electricity generation.

Table 4.3: Installed capacity in Arctic and Equatorial regions according to GEI scenarios [32].

		2030	**2050**
Arctic region: wind power [GW]	Greenland	0	289
	Norwegian Sea + Barents Sea	0	122
	Kara Sea	6	137
	Bering Strait	6	137
Equatorial region: solar power [GW]	Africa	232	1712
	Middle East	76	951
	Australia	0	381
	Latin America	23	381

For GEI scenario, different hypotheses in terms of cost variables were done compared to BAU. More precisely, LCOEs for combustible fuels were increased by 20% with respect to 2014 values, to push a wider deployment of RES-based electricity. LCOEs for geothermal, nuclear and other sources were maintained equal to 2014 values, while for the renewables (i.e. hydro, solar, and wind), the initial LCOEs were reduced by 38% and 43% for 2030 and 2050, respectively. As for the LCOE values for the new renewable installations in the Arctic and Equatorial regions, the following assumptions were done. For the solar additional installations, the values reported in Ref. [188] were considered: LCOE was assumed equal to 50 USD$/MWh and 34 USD$/MWh for 2030 and 2050, respectively. As for wind power installation in the Arctic region, the projected Russian LCOEs were considered valid, due to geographical proximity; the assumed values were equal to 55.8 USD$/MWh and 51.3 USD$/MWh for 2030 and 2050.

The interconnection infrastructure reported in Figure 4.2 and Figure 4.3 was assumed to be in place in all scenario-based models, with the scope of comparing the results with the same grid infrastructure. The interconnections with the Arctic region (i.e Bering Strait, Greenland, Barents Sea and Kara Sea) were assumed based on Ref. [32]. Wind installed capacities in these buses were different from zero only for the GEI scenarios in 2030 and 2050; however, for all the models, the infrastructure was assumed to be standing for transferring electricity among the world regions.

4.1.5 Key findings and discussion

The work aimed to develop an optimization analysis, comparing different projections of electricity demand and generation trends, in turn dependent on specific policy considerations. The comparison was based on a set of multi-dimensional

KPIs, aiming to analyse the effect of different long-term environmental policies on the results, as well as to estimate the potential impacts of a GEI-based scenario.

Among the possible interconnection-related benefits, the development of a global level analysis allows accounting for time differences between the different countries, as well as seasonal diversities among hemispheres. Indeed, using an interconnected electricity system across the world, it is possible to obtain relatively smooth load curves to realize the benefits of peak shaving and valley filling. Figure 4.4 reports the global hourly load profiles for 2014 and for the six scenarios. 2050 GEI scenario represents an extreme solution in terms of electricity demand, as in Ref. [32]; all other scenarios simulate higher demands than the baseline condition. All profiles are almost flat, since the global infrastructure in place allows to take advantage of night-day shifts and seasonal differences of the different geographical zones. It is worth mentioning that the analysis here presented was performed for the winter peak load day, assuming it as the highest demanding condition for the Northern Hemisphere (and specifically for Europe). However, due to the impacts that climate change and global warming is having on air conditioning demands (as discussed in Chapter 2), it would be interesting to develop the same analyses for the summer peak load, to visualize if possible power flows reverse would occur.

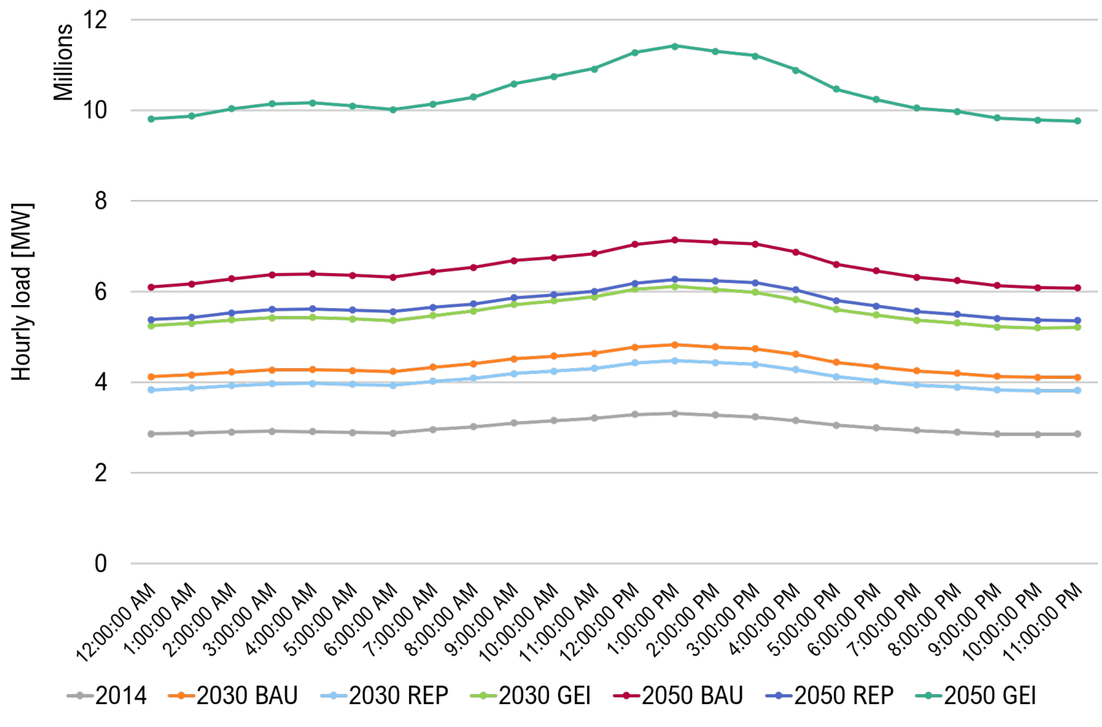

Figure 4.4: Global hourly load profiles for 2014 and six scenarios.

From the energy standpoint, total electricity consumption for winter peaks in the different scenarios is reported in Figure 4.5. REP scenario for 2030 and 2050 considers the lowest increment projections, while GEI represents the most extreme scenario, especially for 2050, when the projections of demand growth from Ref. [32] were extremely high. The differences between REP and BAU suggest the effects of policy actions in terms of energy consumption reduction (i.e. higher energy efficiency and diffusion low-carbon technologies at end-use level, diffusion of practices of energy labelling, etc.) and are more visible in the long-term (2050).

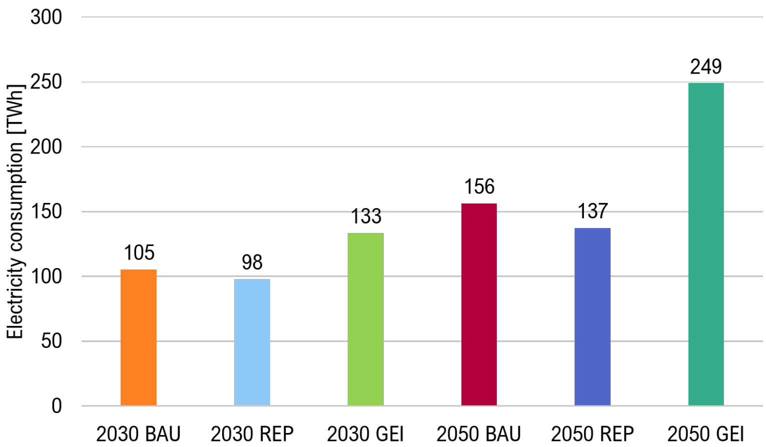

Figure 4.5: Total electricity consumption for the six scenarios.

The regional-level analysis allowed to deepen the local behaviours in terms of electricity generation and demand, and in particular in relation to the NET indicator, as depicted in Figure 4.6. A NET value greater than zero for a specific region corresponds to a local electricity generation higher than the consumption, and thus it is representative of exporting areas. According to the graph, countries with abundant resources, cheap technological implementations and low LCOEs, as China (CHN) and North America (NAC), would become the main energy exporters from a global perspective. For the importing zones, instead negative NET indicators are obtained (regional electricity generation is lower than consumption). This situation occurs for all scenarios in European Union (EU), Eastern Europe and Eurasia (EEE), Japan (JPN), Eastern Asia (EAS) and Other Asian countries (OAS).

The regional conditions appear relatively stable in the different scenarios, with the sole exception of GEI scenarios (both 2030 and 2050), in which the highest demanding conditions provoke some variations in the global market conditions. In particular, in EU, the difference between generation and consumption is reduced, and thus also the NET indicator; due to the higher electrical load, indeed, in this area, more generators are activated, thus reducing the amount of electricity to be imported. Conversely, situation reverses in NAC and CHN, since, due to the assumed demand growth, these countries need to rely on electricity imports (mainly from the new-installed RES plants envisioned by the GEI vision [32]) to meet their

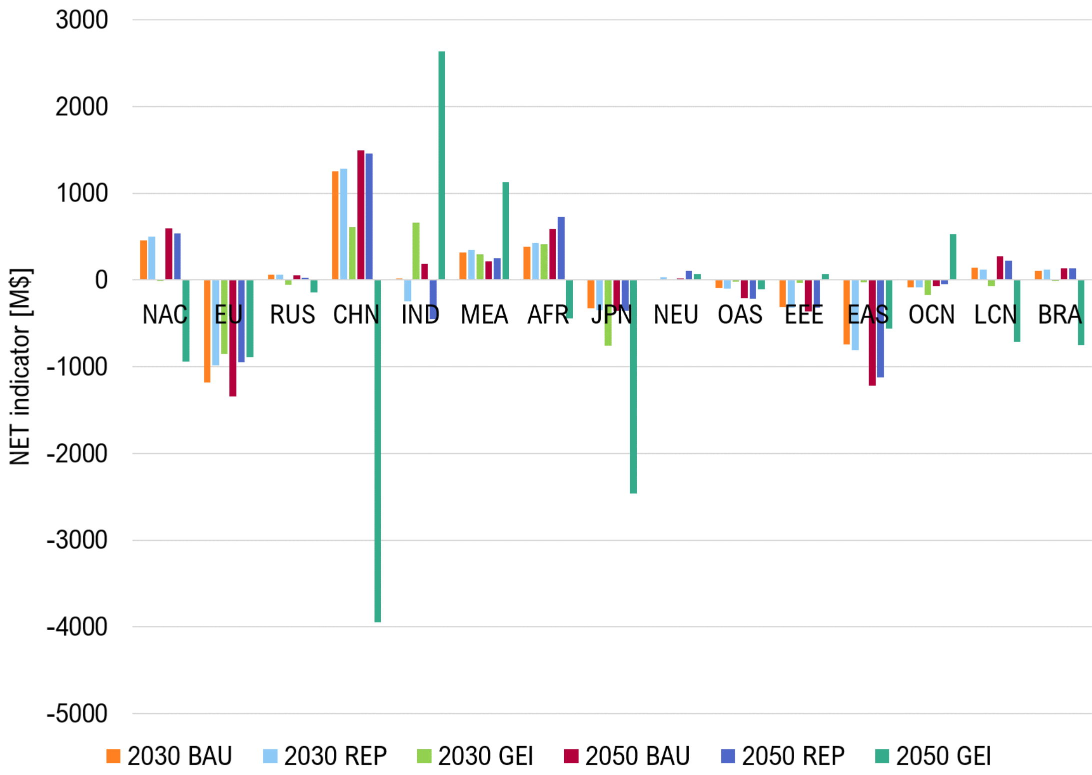

Figure 4.6: Net electricity trading indicator per each world region for the six scenarios.

loads. India (IND), Oceania (OCN) and Middle East (MEA) represent the only exceptions, due to a combination of higher projections of generation and demand growth (especially for India) and higher electricity generation from additional GEI-based solar installations (in OCN and MEA).

Figure 4.7 compares the developed scenarios in terms of costs of generating electricity at regional level. From the graph, it clearly appears the disproportion of the 2050 GEI scenario with respect to the others; due to the high demanding conditions, which request all regions to activate the entire set of generators at disposal, hourly LMPs of the unified global market are significantly higher than those of the other scenarios, thus increasing the costs of generating electricity for all countries, with more effects on the regions characterized by high loads (i.e. CHN, NAC, EAS, AFR). Also in 2030 GEI scenario is characterized by the highest conditions in terms of generation cost. For all time horizons, REP scenario always represents the most economically convenient condition, due to lower growth rates for electricity generation and demand.

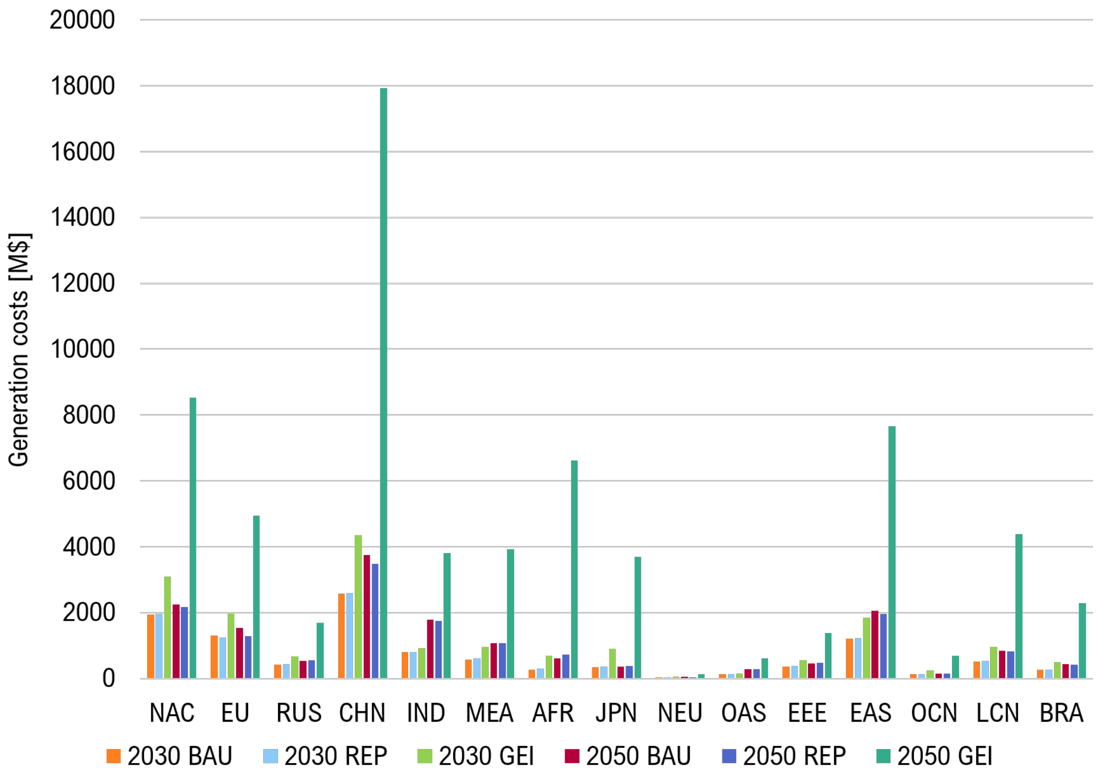

Figure 4.7: Generation costs per each world region for the six scenarios.

The optimization allowed to evaluate the highest needed interconnection capacities for the different scenarios, which were defined on the basis of the maximum power flow during the 24 hours of simulation for the whole set of considered transmission lines (as reported in Table 4.4). As a consequence of the previous considerations, it is clear that 2050 GEI scenario requests the highest capacities, while REP and BAU scenarios are always characterized by low differences, related to the diverse projections of electricity generation and demand, based on literature scenarios [181]. REP scenarios, both for 2030 and 2050, represent the lowest demanding conditions, correlated to the positive effects of climate change mitigation policies compared to BAU scenarios.

Finally, to assess the environmental impacts caused by the different scenarios, GHG emissions from electricity generation were calculated, in terms of CO_{2eq} emissions. A default global emission factor equal to 500 $g_{CO_{2}eq}/kWh$ was considered for the calculation [189]. Figure 4.8 shows the overall emissions for the six scenarios. REP represents always the condition with the lowest emissions, justified by the higher committent in terms of mitigation policies; indeed, in both 2030 and 2050, according to WEO projections [181], the installed capacities of combustible fuels for BAU scenarios are higher than those of REP. Coming to GEI-based analyses, in

Table 4.4: Power corridors interconnection capacities (expressed in GW) for the six scenarios.

HVDC Inter-connection	**2030 BAU**	**2030 REP**	**2030 GEI**	**2050 BAU**	**2050 REP**	**2050 GEI**
Bering Strait - NAC	0	0	70	0	0	280
NAC - Greenland	430	380	90	560	450	360
NAC - LCN	150	140	80	230	200	410
EU - RUS	90	70	80	100	60	270
EU - CHN	130	80	200	120	60	260
EU - AFR	190	170	220	240	220	730
Barents Sea - EU	0	0	0	0	0	70
NEU - EU	240	210	80	300	270	170
EU - EEE	50	40	110	50	60	110
RUS - CHN	60	40	130	70	60	280
JPN - RUS	100	100	130	120	110	340
Kara Sea - RUS	0	0	10	0	0	70
RUS - Bering Strait	0	0	70	0	0	210
NEU - RUS	200	190	50	270	230	190
EEE - RUS	60	60	60	80	80	170
CHN - IND	140	140	220	190	230	660
CHN - JPN	100	90	200	110	80	280
OAS - CHN	40	30	70	60	50	320
EEE - CHN	80	60	100	90	40	190
CHN - EAS	470	420	130	760	530	260
MEA - IND	110	160	90	90	230	290
AFR - MEA	50	70	110	100	170	340
OAS - MEA	120	120	140	160	150	520
Greenland - NEU	430	380	90	560	450	220
EEE - OAS	90	70	80	80	60	200
EAS - OCN	50	40	70	40	30	290
LCN - BRA	60	60	30	80	70	160

both milestone years, for the peak load day, GHG emissions are higher if compared to the other conditions; these results are most probably connected to a prominent end-uses electrification, which leads to a massive increase of electricity demands and inevitably induces the shifting of GHG emissions from other sectors/commodities to the power sector. For this reason, despite the exploitation of wind and solar power installations in Arctic and Equatorial regions, the demand projections still require to generate electricity from combustible fuels plants.

In order to analyse the possible benefits and challenges connected to the GEI

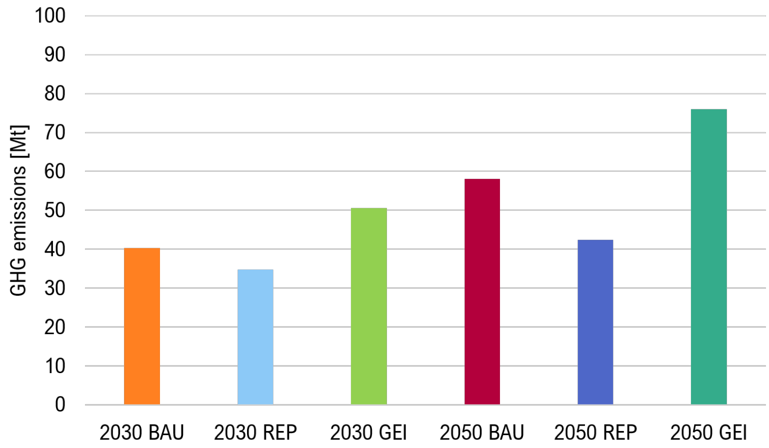

Figure 4.8: Global GHG emissions for the six scenarios.

implementation, further study was developed, aiming to compare the scenarios in case interconnections are not in place. The condition of absence of interconnection structure was assumed as an ideal and extreme situation of complete balance between generation and consumption in all geographical zones (each considered as independent and isolated from the others, i.e. not admitting importing or exporting power flows among them). For each world region, hourly loads were satisfied by progressively introducing in the market the generators with the lowest LCOEs. In case the total installed generation of a region is not enough to meet the load, an additional generation from combustible fuels was assumed to balance the demand. This condition occurred mainly in GEI scenarios, in which, due to the absence of the electricity generation from Arctic wind installations (which cannot be traded without the interconnection structure in place), some regions experience the need for additional installed capacity to meet the load. In this ideal situation, the cost of generating electricity was calculated according to Eq. 4.6, where $LMP(i,t)$ values vary per each geographical zone and hourly time-step:

$$C_g^{w/o}(i) = \sum_{t=1}^{24} C(i,t) \cdot LMP(i,t) \tag{4.6}$$

Figure 4.9 shows the delta costs, computed per each region as the differences between the costs with interconnections (Eq. 4.5) and without interconnections (Eq. 4.6). Negative values correspond to situations in which the scenarios with interconnections result more economically convenient. According to Figure 4.9, BAU and REP scenarios are characterized by balanced situations between the two extreme cases for almost all countries; in particular, for the importing countries, like EU, negative delta costs are measured, meaning that the ideal situation of absence of interconnection structure is not beneficial for these regions. Conversely, for GEI scenarios, positive values are obtained for almost all zones. It is important to consider that, in this latter scenario, the wind installations in the Arctic region were not accounted, while the solar installations in the existing buses (i.e. Africa, Middle East, Oceania, and Latin America) were considered.

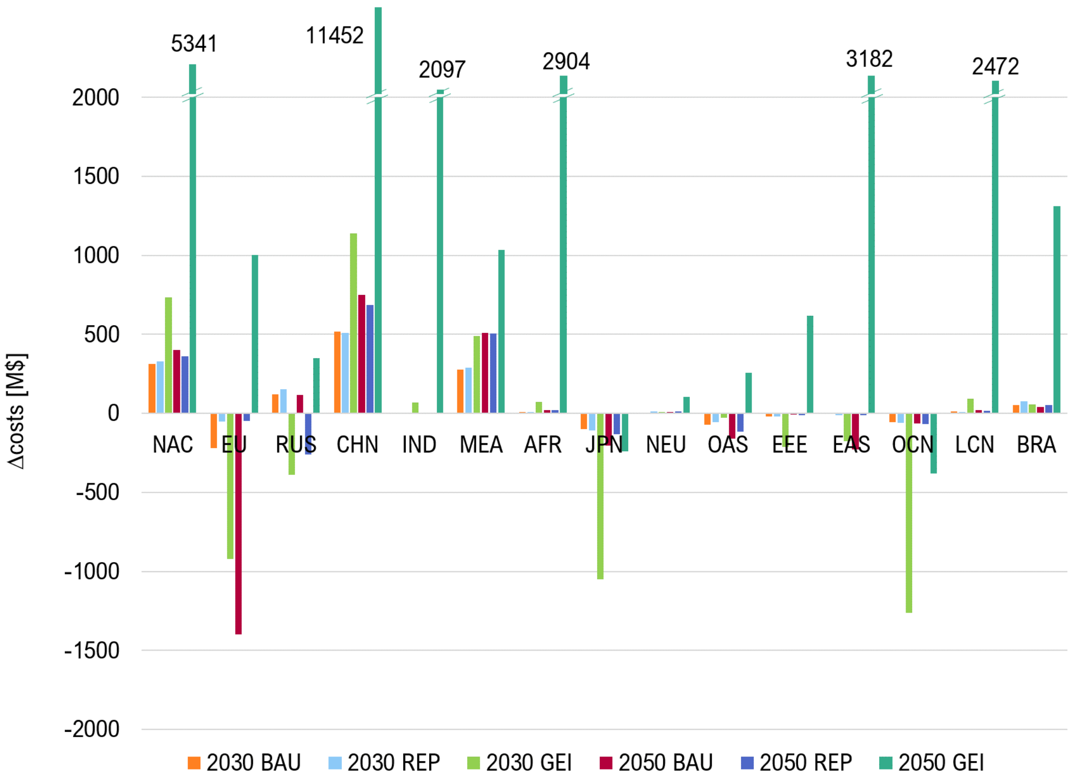

Figure 4.9: Delta cost between the cases with and without interconnection infrastructure in place, for each world region and for the six scenarios.

Concerning the environmental dimension, to compare the solutions with and without interconnections, Figure 4.10 represents the global GHG emissions for the six scenarios, for the two cases; the bars with solid colours represent the scenarios with interconnections, while the barred ones represent the scenarios without interconnections in place. In general, GHG emissions for the cases with interconnections are lower than those without interconnections. The greatest differences are obtained for the GEI scenarios, since, in case of no interconnections in place, the demand projections are high, thus requesting the deployment of all generators to meet the load, including the eventual additional capacity of fossil plants. Emissions were calculated only for the electricity generation from combustible fuels; in almost all scenarios, generation from combustible fuels is compensated between the conditions with and without interconnections, being it only shifted in the different regions. Due to the high environmental impact of the GEI vision, an ideal scenario was developed, by modifying the load conditions. For the 2030 GEI scenario,

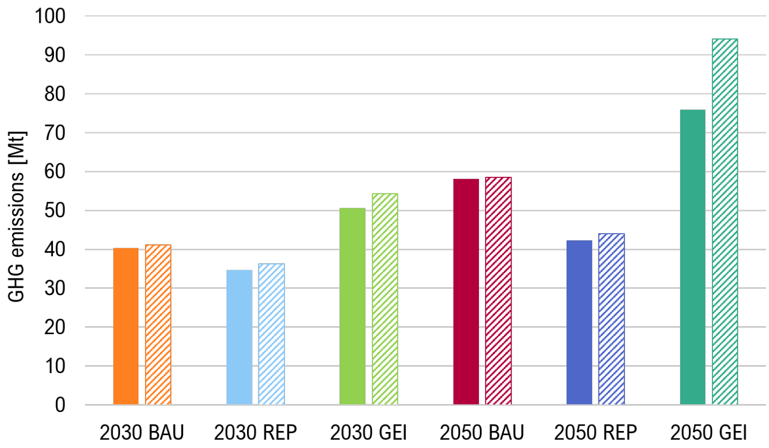

Figure 4.10: Global GHG emissions for the cases with (solid colours) and without (barred colours) interconnections for the six scenarios.

keeping fixed the electricity generation from renewable sources, the total demand was set as in the 2030 REP scenario. The same assumption was done for the 2050 GEI scenario (setting its demand as in 2050 REP). The obtained environmental results are shown in Figure 4.11. Both 2030 and 2050 GEI emissions are reduced with respect to Figure 4.10, highlighting how the emissions of these scenarios could become even lower than the REP scenarios, thanks to a more RES-based electricity mix.

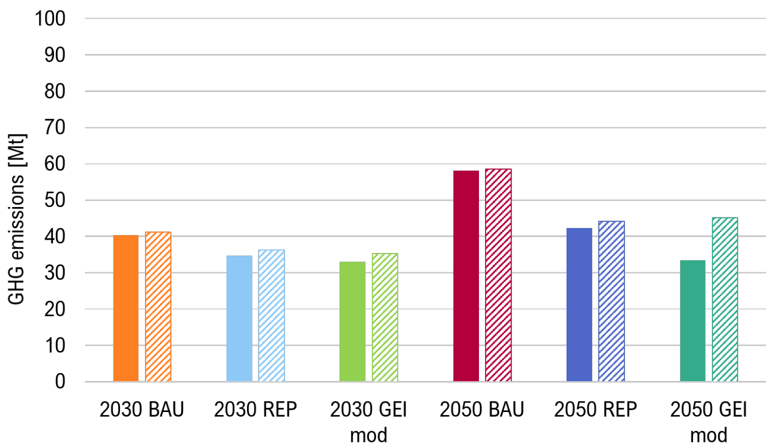

Figure 4.11: Global GHG emissions for the cases with (solid colours) and without (barred colours) interconnections for the six scenarios, with reduced load for GEI.

4.1.6 Conclusions and further investigation

The realization of a GEI-based energy scenario clearly involves a structural modification of the global energy systems. In this application, a new power system paradigm, based on the construction of large-scale interconnections in order to transfer clean energy from RES-rich areas to major load centres, was investigated through optimization analyses. A simplified global electrical network was modelled and simulated with OPF approach, performing hourly simulations. The model comprises 15 nodes, one per each identified geographical area, and 4 additional nodes for the wind installations in the Arctic region, according to Liu's projections [32]. Six scenarios were developed for 2030 and 2050, assuming diverse electricity generation and demand trends, in turn associated to different mitigation policies. Optimization was performed assuming the presence of an interconnected infrastructure and of a global electricity market, allowing to transfer electricity among the interconnected regions, without network constraints. The results allowed to state that the presence of large-scale interconnections would stimulate the electricity trading at global level, improving the access to remote RES-rich areas. In particular, the large-scale model allowed to consider and simulate a condition of favourable deployment of RES in some regions (coherently with Liu's assumptions), as well as to evaluate the corresponding power flows from regions with favourable RES potentials to others.

Direct economic and environmental impacts of the interconnected scenarios were quantitatively assessed using a set of regional- and global-scale KPIs, belonging to energy-technical, socio-economic and environmental domains, which were designed to compare the six scenarios of large-scale interconnections (three for 2030 and three for 2050), among which those built in line with GEI assumptions.

Despite the interesting assessment of the potentialities and implications of a global power network, this application presents some limitations. From the technical standpoint, the model simulated an ideal solution, based on the presence of enhanced power grids, capable of dissipating the massive power flows from intercontinental power corridors, and this assumption is far from the reality; no transmission technical constraints were considered, no investment and operation costs associated to the transmission network were accounted and the analysis did not take into consideration any storage or reserves requirements. Furthermore, non-technical factors were not taken into account in the development of the model, assuming the realization of the scenarios as a pure techno-economic transition, without considering possible barriers, obstacles or interests in their development.

In this sense, the developed socio-economic analyses, in terms of net electricity trading indicator and delta costs between scenarios with and without interconnections, were propaedeutic in highlighting how global energy interconnections, for their realization, need to be tackled not just in technological terms, but with a multi-dimension and multi-perspective approach. As stated by Bompard et al., even though technical solutions already exist, the major concerns and open questions that this energy system paradigm arises are market- and policy-oriented [26]. Particularly, the management and sovereignty of this system are still open issues, as well as the problem of cost and benefit allocations and the definition of new electricity market schemes [26]. The implementation of GEI, moreover, would need great cooperation among countries, possibly arising new geopolitical issues associated to RES trading, which will imply rules different from those in force for the trade of fossil fuels [26]. Grid codes and electricity pricing mechanism should be redesigned, and all these considerations ask for a robust policy framework, global-based and aligned with major climate goals. To do this, integrated assessments are needed, having in mind that energy systems are intrinsically related to economic, social, and political dimensions. Techno-economic analyses, usually used for dealing with power transmission expansion planning studies, cannot be separated by socio-economic developments and transitions. Long-term energy scenarios need to be further improved, to be used as a support for policy-decision making and strategy development, by linking energy systems considerations with wider socio-economic aspects. Further work is needed in this regard, to study the relationships between technical systems with other non-technical aspects (i.e. socio-economic, political, financial) and to define the key influencing parameters for describing and modelling this complex system. Moreover, tools and models should be thought to couple technical aspects with non-technical ones in a single modelling framework. These elements will be further discussed in the following section.

4.2 Multi-dimensional energy planning at European scale

4.2.1 Overview

Energy systems are enclosed in intricate social, economic and political patterns, and, hence, long-term transitions need to be handled with a multi-disciplinary vision and to be supported by decision-making approaches able to integrate all the various facets of energy issues and the possible perspectives and interests of the involved stakeholders. Transmission expansion planning is not exempt from these considerations and, to tackle this challenge, this application proposes a novel approach, which combines traditional power system modelling with the use of evaluation tools (i.e. decision-making support tools). This section moves the lens from a global scale to a European perspective, aiming to investigate the capability of the European network to accommodate the power flows simulated with the GEI scenarios in two milestone years (2030 and 2050), using the results of the global grid analysis performed in section 4.1. The hybrid A'WOT method, derived from the integration of pure SWOT analysis with the Analytic Hierarchy Process multi-criteria method, is used as a tool to guide the decision-making process in the case of large-scale power expansion planning and to support the power system modelling phase. In particular, the work aims to evaluate the possible key criteria influencing the planning of long-distance electricity interconnections between Europe and its surrounding areas and to apply the hybrid A'WOT method to help decision-makers in defining the most appropriate interconnection strategies, highlighting opportunities and obstacles for their realization. In detail, the A'WOT method is applied to support the planning of electricity interconnections between Europe and its surrounding areas (i.e. Africa, Arctic region, Russia, Eurasia, China), aiming to identify the European countries most suitable for hosting intercontinental interconnections, from a multi-criteria perspective. These results are then used as input to a preliminary optimization approach, to identify the optimal allocation of the accessing nodes in each country and to estimate the optimal power flows distribution in the European network, under the premises of a GEI scenario.

Keywords Multi-criteria decision analysis, hybrid A'WOT method, Analytic Hierarchy Process, Global Energy Interconnection, large-scale transmission expansion, policy decision-making, European power grid.

Declaration The topics described in this chapter were previously published in the following publications:

- **G. Crespi**, C. Becchio, M. Bottero, T. Huang, E. Bompard, S.P. Corgnati, *Multi-criteria approach to transmission expansion planning in Europe*, Proceedings of

Energy for Sustainability Conference 2019: Designing a Sustainable Future, 24-26 July 2019 [88].

- Z. Han, **G. Crespi**, T. Huang, X. Tan, Z. Ma, F. Yang, H. Huang, *Development of European Power Grid and its Compatibility with Global Energy Interconnection*, Electric Power Construction 41, p. 1-11, 2020 [79].

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4.2.2 Background

The construction of a globally interconnected power system will have consequences for Europe, which could benefit from the connection to a UHVDC global network, and for this reason research on the interconnection between Europe and its surrounding areas has spread in recent years [80, 178, 190, 191, 192, 193]. To support this, the European policy framework needs to bring more regulatory certainty, partially already obtained thanks to the introduction of national energy and climate plans, and should better encourage investments in the energy sector, mainly related to the increase of renewable energy generation and the improvement of energy efficiency at end-use level [194]. The highlighted objectives, on the one hand, will contribute to render variable renewable energy and diverse flexibility sources (i.e. demand response, storage) essential elements in future electricity systems [78]; on the other hand, they will boost the necessities and chances for cross-border electricity exchange, increasing power flows across countries and, thus, asking for a higher interconnected European electricity system [76]. The topic has interested several policy makers and academicians, introducing the idea of a European integrated power grid, where electricity demand and generation could be balanced among different countries. The idea of electricity interconnection within Europe is of interest especially in terms of electricity market redefinition and management, as confirmed by the European policy agenda. Concerning the electricity market, the European Commission has imposed a 15% interconnection target by 2030, following on from the previous 10% target for 2020 [195], meaning that each Member State should guarantee a power grid able to transfer at least 15% of its electrical production to surrounding countries [195]. Even though, in recent years, strong improvements have been done for the European electricity network interconnection, additional efforts are needed to cope with the expected transition towards renewables [70]. Moreover, besides cross-border power interconnections within EU, the research activity aims to explore hypothetical scenarios of GEI implementation from an European perspective, analysing the European possibility to increase interconnections with close areas (e.g. Africa, Russia, China, etc.), in order to further deploy the RES potential at worldwide level, in line with the GEI vision. However, also for Europe, the challenges of an interconnected and RES-based power system need to be carefully addressed, also in line with the transmission expansion and reinforcement projects already planned for 2030 and 2050.

Planning long-distance electricity interconnections requires tools able to help stakeholders exploring the current situation and considering the entire set of conflicting criteria that can characterize and influence the planning process. As reported by Crespi et al. [88], "*as pointed by Tenggren et al. [196], research on grid development has been so far dominated by energy economics and power system engineering, looking at it as an issue related to regulations, market structure and investment costs. In this sense, model-based scenarios are typically used, performing techno-economic simulations to study effective strategies to minimize investment and operation costs. However, this traditional approach presents some limitations, as defined by Geels et al. [197]. Firstly, little attention is devoted to actors and actions that can influence systems transitions, as well as to non-technical factors (e.g. social acceptance, political stability, geopolitics, etc.) that can affect the realization of the transformation plans. Moreover, model-based scenarios seem to not consider the stakeholders' influence on the planning process [197].*

Generally, non-technical factors, as the interaction between stakeholders and political institutions or socio-economic aspects, are difficult to describe in mathematical terms and to be inserted as input in engineering model-based scenarios. Transmission expansion planning is not excluded from this consideration" [88]. Indeed, power system transformations involve social, economic, political and environmental concerns that cannot be neglected in future scenarios analysis. In the interest of science-based decision-making, apart from technical issues, it is of fundamental importance to include in the evaluation all influencing factors, as well as to assess typical qualitative factors (i.e. geopolitical risk, social acceptance, stakeholder engagement, etc.) that can influence the phenomenon under investigation. In this sense, purely techno-economic-based decisions do not always represent the right approach, neglecting various non-technical aspects, which conversely should play a not trivial role in the decision-making process. Indeed, the issue of power expansion to create more interconnected electricity systems is challenging, and its conceptualization is particularly difficult, especially when the expansion embraces vast territories, as in the case of GEI. As well stated in Ref. [198], the power expansion planning topic is complex and multi-dimensional, characterized by various and contrasting criteria, each expressing the interests and objectives of the involved stakeholders in the planning process. Appropriate multi-dimensional methods could be beneficial also for large-scale planning problems (as GEI is), which need common high-level strategical decisions to be taken at regional, national and international scales. Moreover, stakeholders' interests, as well as their perceived barriers, need to be accounted to define the best expansion strategy also considering the influence that stakeholders might have in its successful realization or failure [88].

It is against this background that decision-making support tools are recommendable. Indeed, being instruments capable to integrate different elements, belonging to diverse and often contrasting domains, these methods represent powerful solutions to guide energy policy makers to articulate plans representing the best compromises between multiple perspectives and objectives [15]. In order to respond to the need to integrate non-technical parameters into power system models, this section aims to provide a first attempt of integration of multi-criteria evaluation tools with traditional power system modelling.

The previous application at global scale, formerly reported in section 4.1, was used as starting point for developing further investigation on power grid development plans, focusing on the European situation, and on their capability to hypothetically allocate the power flows predicted within the GEI framework. In this context, the latest Ten Year Network Development Plan (TYNDP) [199] from the European Network of Transmission System Operators for Electricity (ENTSO-E) forecasted the future European network plans up to 2040, considering three possible pathways of decarbonization to meet the climate and energy targets at EU level. This application aimed to discuss the compatibility of official future TYNDP plans, in case a GEI-based scenario of intense intercontinental power corridors is considered. As reported in Ref. [79], official European network plans are usually based on the combination of a moderate growth of electricity demand, a progressive RES penetration and an increase of local installation. Conversely, as already discussed in sections 4.1, GEI vision is based on a significant increase of electricity demand and a strong penetration of RES technologies, mainly installed in remote areas, to exploit the high solar and wind potential in the Equatorial and Arctic regions [32]. According to the GEI vision (and confirmed by the preliminary global modelling described in section 4.1), a significant part of EU electricity demand would be met with RES and transferred through intercontinental power corridors. Therefore, this condition might introduce power flows in the European network that are beyond the TYNDP considerations and that would likely cause internal congestions.

Starting from these considerations, this section describes the application performed at European scale, with the scope of evaluating the European readiness to an ideal GEI scenario of intense intercontinental power corridors, starting from the simulations performed at global scale and reported in section 4.1 and attempting to combine traditional power system modelling with the operational research methods. In order to integrate into power system modelling also non-technical aspects, appropriate decision-making support tools are reviewed and developed, aiming to provide usable outcomes to be exploited as inputs for the modelling phase.

Use of decision-making tools in energy planning

Among the wide set of available methods, SWOT analysis is a qualitative evaluation tool typically employed for strategic planning and management. It is a powerful way to provide a snapshot of a decision situation, defining all its influencing factors (named as strategic factors), divided into four categories: strengths, weaknesses, opportunities and threats. The first ones are defined as internal factors, being directly controllable, while the latter are considered as external factors and, thus, not fully under direct control [200]. The knowledge of the entire set of strategic factors that can influence a decision process is fundamental to better manage it. The final goal of the SWOT analysis, indeed, is to develop and adopt a strategy representing a good compromise between internal and external strategic factors [201], allowing, on the one side, to maximize strengths and opportunities and, on the other side, to minimize weaknesses and threats; for this reason, SWOT analysis represents an excellent basis for strategic planning in different fields. However, it presents some limitations. Among them, it is important to cite that SWOT analysis allows pinpointing the number of strategic factors, but it does not provide the basis for defining the most significant group of factors or their relevance, being the analysis purely qualitative [201]. To overcome these limits and enhance the use of SWOT analysis as a support for the decision-making process, a branch of operational research has worked on the combination of SWOT analysis with other existing strategic planning tools [202], among which the Multi-Criteria Decision Analysis (MCDA) methods [203, 204]. As defined by Blanco et al., MCDA "has the advantage of offering tools for the better understanding of intrinsic characteristics of the decision problem, encourage the role of participants in the decision-making process, enable compromise and collective decisions, and provide transparency to the insights of the model and analysis" [112]. There exists a variety of MCDA tools and techniques, with different approaches of definition of the decision contexts, disaggregation of complex problems and weighting technique for estimating the final scores of the alternative strategies under investigation.

Among the diverse combined SWOT-MCDA tools [202], attention is here devoted to the hybrid A'WOT method, which integrates the SWOT analysis with a well-established multi-criteria method, the Analytic Hierarchy Process (AHP), one of the most widely used MCDA methods [112]. AHP was originally developed by Thomas L. Saaty in the 1970s [205]; it is a descriptive decision analysis method [206], suitable for helping decision-makers in finding the solutions that best suit their goals and understanding of the problem, instead of defining a unique "correct" decision [112]. In particular, the AHP approach is particularly useful to provide an inclusive and coherent framework for structuring the decision-context and for ranking the decision alternatives, without providing a single answer to the problem [112]. The joint application of the two evaluation tools is profitable, allowing to benefit from both approaches. Indeed, as mentioned before, SWOT is suitable for framing the decision context, depicting strengths, weaknesses, opportunities and threats of the decision-making process, and for selecting the appropriate criteria on which the comparison is based. On the other hand, AHP is particularly useful for quantitatively examining the SWOT factors and for including stakeholders' judgments and personal preferences in the decision process. Moreover, AHP is easy to be applied, also in its joint application with the SWOT approach [201].

Based on the results of the main literature-reviewed applications, it appears that A'WOT method allows to improve the knowledge of the decision-making processes, as well as to force decision-makers to express preferences and judgements, by weighting the different strategic factors, and, thus, to look more deeply to the decision problems [201]. Moreover, thanks to its characteristics, the A'WOT method is suitable for several strategic planning purposes [201]. Indeed, since its first application in the forest planning field [201], the hybrid method has been applied in literature to several macro-areas. As denoted by the variety of applications, the method is versatile and could be used either to identify strategies in case in which strategic options are not yet defined, or to compare different strategic alternatives, to evaluate which may represent the best compromise between the SWOT factors [201].

In line with the above, in this section the hybrid A'WOT method is tested as a possible instrument for guiding ad supporting decision-makers in the field of energy planning (i.e. large-scale interconnections development). Generally, decision-making tools in the energy field are particularly used when dealing with strategies involving different stakeholders, as the afore-mentioned theme of transmission expansion. As pointed by Miller et al., indeed, energy policy asks for participative and holistic decision-making methods able to consider and explore the cross-cutting nature of energy issues [15]. Multi-criteria methods, in different forms, have become increasingly popular in the energy decision-making over the years [206]; moreover, energy planning is usually based on high-level strategic decisions, to deal with which SWOT analysis has been widely used [112]. Therefore, starting from a decision-making tool well-established in the policy context and familiar among stakeholders, its combination with multi-criteria methods can help in framing more appropriate decision processes and energy policies. Few examples of the hybrid A'WOT method within the energy area are assessed in literature [207, 208], and most are devoted to specific applications. For the sake of exemplification, Brudermann et al. used A'WOT for exploring the future possible contribution of agricultural biogas plants to sustainable energy supply goals [209]; Posch et al. investigated energy management issues in paper and pulp companies [210]; Reinsberger et al. used the method to evaluate the role of PV plants in future energy transition [211]. Deepening more on the energy planning field, Bas presented an application of a SWOT-fuzzy TOPSIS combined with AHP for analysing electricity supply chain strategies in Turkey [207], while Zare et al. dealt with the Iran case, using the same methodological approach [208]. Blanco et al. presented an application of the hybrid method for comparing different policy options for hydro-power surplus utilization in Paraguay [112]. More recently, Stojčetović et al. applied the SWOT-AHP integrated model for the municipality of Štrpce (Serbia) to snapshot its current energy and electricity situation and to compare potential strategies for improving its energy security [212]. Finally, Papapostolou et al. presented an application of an AHP-SWOT-Fuzzy TOPSIS approach for studying the strategies of cross-border RES cooperation between EU countries and the closest developing countries, providing applications for Morocco and Egypt [190].

To the best of the candidate's knowledge, even though some examples of application of the A'WOT method for energy planning and policy decision-making are present in literature, most are restricted to local or national level, while little attention is devoted to large-scale (i.e. international, global) analyses. In order to explore the use of the hybrid methodology to support energy planning at broader territorial scales, the A'WOT method is here employed as a possible solution for guiding decision-makers in this field. To this purpose, high-level and national-based criteria are introduced to create a large-scale decision-making tool, to be potentially used at different international scales. In detail, the work makes use of the SWOT analysis to explore the internal and external factors that can positively or negatively influence the planning of electricity interconnections with Europe and its main surrounding areas, while its combination with the AHP allows to quantify them and, thus, to provide a commensurable assessment of the proposed strategic alternatives. The method, tested using specific case study analyses, could be used to guide decision-makers in defining the most appropriate strategies for European intercontinental interconnections, highlighting possible associated opportunities and obstacles that can arise.

In line with the global scale analysis described in section 4.1, the hybrid method is deployed as a decision-making support instrument for supporting the planning of the electricity interconnections of Europe with the five main surrounding areas (i.e. Africa, Arctic region, Russia, Eurasia and China) previously identified. Five A'WOT models are developed, each studying the interconnection of Europe with one of the cited areas. The objective of each model is to define and rank the European countries most suitable for hosting the intercontinental corridors, according to various factors (i.e. technical, social, economic, politic). The most appropriate strategic options, identified in relation to the analysis of the current energy condition of the selected EU alternatives, are identified through experts' judgments.

4.2.3 Methodology

This application uses a multi-layer methodological approach to transmission expansion planning, aiming to couple the typical techno-economic elements of power system modelling with non-technical parameters, usually not accounted in traditional analyses. In detail, the methodological approach deploys the outcomes of the application of the hybrid A'WOT method as input to the power system modelling exercise, allowing to take into account the possible environmental, political, social and economical variables that can influence the transmission expansion planning process. The methodology is structured around the following main steps, as summarized in Figure 4.12:

- **study: definition of relevant criteria and analysis of the involved stakeholders**. The main macro-players potentially involved in the transmission expansion planning process are identified, analysing their possible interests and concerns on the realization of the project, allowing the definition of the main criteria useful for describing and driving it.
- **synthesize and support: development of the hybrid A'WOT method**. The hybrid A'WOT approach is applied to combine the multi-dimensional criteria in order to rank the energy planning strategies. Specifically, based on the A'WOT development, the European countries under investigation can be ranked in line with their suitability for hosting the intercontinental interconnections.
- **study: European grid modelling**. A European grid modelling is developed, collecting the techno-economic parameters required for the modelling of the baseline condition. Moreover, to simulate a GEI-based scenario, techno-economic input parameters are projected for 2030 and 2050, in line with section 4.1.
- **simulate and support: optimization**. A multi-objective optimization approach to merge the outcomes of the A'WOT approach with the grid modelling is performed, aiming to optimally identify the landing points of the interconnectors within each European country. Starting from the application reported in section 4.1, the analysis is performed for the peak load hour and results are presented in the form of regional- and national-based KPIs.

Study: definition of relevant criteria and analysis of the involved stakeholders

Once defined the objective and the focus of the study (i.e. a specific project to be realized, a policy to be discussed, etc.), in order to use a SWOT-MCDA method tailored also on stakeholders' perspectives, it is fundamental to first carry out a literature review, aiming to highlight the main actors involved in the planning process. This step is crucial to identify stakeholders' interests, as well as to evaluate the main obstacles they might perceive in the realization of the project. This step aims to explore people or institutions having a significant role in the decisional process [88]. Indeed, the definition of the relevant stakeholders is fundamental in order to create a strategy able to line up and consider all the specific interests and needs and to avoid conflicts [213]. In this analysis, this step is propaedeutic to the

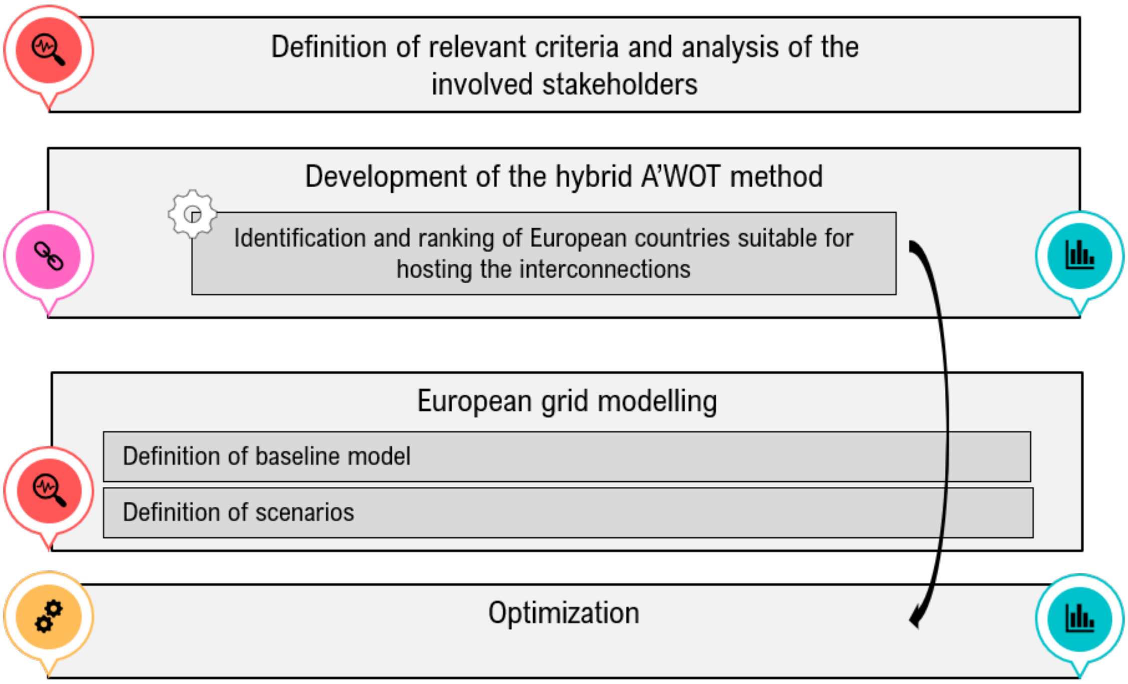


Figure 4.12: Main methodological steps.

definition of the most relevant criteria and indicators able to describe the problem from a multiple perspective, in order to be introduced and assessed in the MCDA procedure.

Synthesize and support: development of A'WOT method

Once defined goal and criteria, A'WOT method can be developed. In detail, when combining AHP and SWOT analysis, the typical AHP procedure is used, which is based on three fundamental principles [205]: 1) decomposition of the problem into a hierarchical structure, composed by (from top to bottom) the initial goal, a set of criteria and sub-criteria, and the alternatives to be compared (see Figure 4.13); 2) judgment of alternatives and criteria through pairwise comparison technique; 3) synthesis of involved experts' preferences [214]. Each MCDA technique uses its own weighting method; in the case of AHP, the approach used is the weighted sum. Specifically, once collected the weights from the experts' pairwise comparison approach, each performance is multiplied by its weight, and the overall score is obtained by summing the obtained weighted performances. The best alternative in the final ranking is the one obtaining the highest score [206] compared to the others competing options. In applying the hybrid A'WOT, the SWOT analysis precedes the AHP steps, since the criteria and sub-criteria for the AHP are organized as the components of the typical SWOT four-quadrant chart. The main steps of the

A'WOT methodology are summarized below [202].

Step 1: Establishing the decision context and identifying the alternatives The first step of the process consists in the decomposition of the decision problem into a hierarchy and in the definition of the goal of the analysis. In this phase, it is important to define the finite set of alternatives (no more than 9) that decision-makers should compare for achieving the objective and that represent the lowest level of the AHP hierarchy (see Figure 4.13). At this stage, an appropriate number of experts should be involved. The direct participation of stakeholders is one of the main advantages of the AHP method, which requires them to express their preferences on the defined criteria and alternatives for achieving the fixed goal [202].

Step 2: Identifying criteria according to SWOT analysis This step consists in the definition of the set of factors to be included in the SWOT analysis, defined as criteria that are "meaningful to the decision-makers for comparing the alternatives" [215]. The number should not exceed 9 factors per each group. In the typical structure of the A'WOT analysis, criteria represent the first intermediate level and are usually subdivided into a group of sub-criteria at the next hierarchical level (see Figure 4.13) [215].

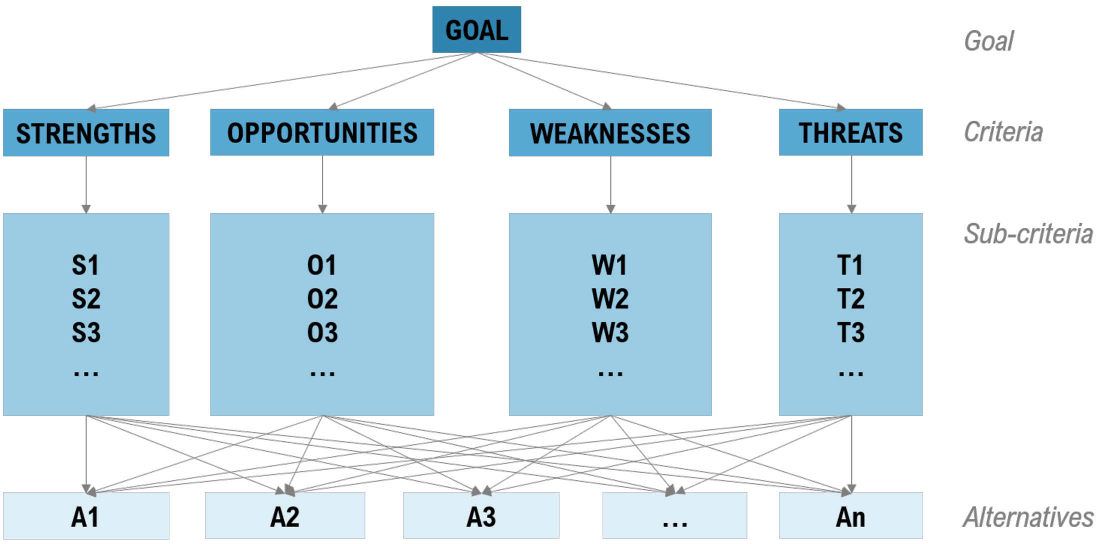


Figure 4.13: Typical structure of hybrid A'WOT method.

Step 3: Weighting the SWOT groups Once the hierarchy is built, the decision elements need to be judged in accordance with the goal of the analysis. The judgments step is performed though pairwise comparison, with the help of a set of experts, who are asked to make the comparisons between two elements at a time, expressing their preferences in line with their contribution to the specific goal [215]. The relative importance of the compared elements is determined on a 9-points scale, named “Saaty’s Fundamental Scale”, reported in Table 4.5 [205]. Firstly, the pairwise comparison between SWOT groups is carried out and two SWOT groups (or criteria) are compared at a time, judging their relative importance with respect to the achievement of the goal; in this case, the question is which criterion is more relevant for the defined goal [215]. For each step, 1 reflects equal preference among the criteria, while 9 indicates an extremely higher preference for one criterion with respect to the compared one [202].

Table 4.5: Saaty’s Fundamental Scale [205].

Value	Definition	Explanation
1	Equally important	Two decision elements equally influence the parent decision element
3	Moderately more important	One decision element is moderately more influential than the other is
5	Much more important	One decision element has more influence than the other does
7	Very much more important	One decision element has significantly more influence over the other
2,4,6,8	Intermediate judgement values	Judgment values between equally, moderately, much, very much and extremely

Step 4: Weighting the SWOT factors within each SWOT group This step consists in the development of the pairwise comparison of the different SWOT factors (sub-criteria) per each of the four SWOT groups [201]. Sub-criteria pairwise comparison is carried out asking experts to express their preference with respect to the upper criterion; as reported by Hummel et al., “in this case, the question is which sub-criterion is more important in fulfilling the covering criterion” [215]. This step allows defining the local priorities of the factors [201]. It is important to note that the AHP methodology admits to compare only sub-criteria belonging to the same cluster, while sub-criteria of different clusters (even if potentially connected or correlated) are not directly compared [201, 202, 215].

Step 5: Scoring the alternatives according to each SWOT factor Finally, pairwise comparisons are used to judge the relative importance of the defined set of alternatives. In this case, alternatives are pairwise compared with respect to each sub-criterion [201]. This step allows the definition of individual rankings of the different alternatives per each stakeholder. It is important to note that if enough quantitative values are considered in the analysis, a direct conversion of the absolute values of the considered alternatives into priorities is possible, through normalization [215, 216]. The judgments performed at each hierarchical level make up pair matrices [214]. Based on experts' judgements, the qualitative attributes of each considered pair of elements from the same level are converted into quantitative attributes stored in a square comparison matrix **A**, as expressed by Eq. 4.7:

$$A = (a_{i,j}), a_{i,j} = \frac{1}{a_{j,i}}, i \neq j; a_{i,j} = 1, i = j; \forall i = 1, 2, ..., m; j = 1, 2, ..., m \quad (4.7)$$

With the help of computer programmes, answers to pairwise comparisons can be directly translated into sets of scores of the different criteria/alternatives on a 0-1 scale. For the AHP method, Saaty suggested the eigenvalue/eigenvector method for the calculation of rankings [205]. This method can be defined as an averaging process, since final weights are defined as "the average of all the possible ways of comparing the scores on the pairwise comparisons" [215]. The step of pairwise comparison between the different sub-criteria (step 4) allows the calculation of the local weights of these sub-criteria, according to the upper criterion (the sum of the local weights of the sub-criteria in any cluster is always equal to the unit). For this step, after comparison matrices are created, the relative weights of the sub-criteria with respect to the upper criterion are computed as the components of the normalized eigenvector associated to the largest eigenvalue (λ_{max}) of their comparison matrix [201, 215]. Local priorities can be estimated by finding the principal eigenvector w of the comparison matrix **A** (Eq. 4.8):

$$Aw = \lambda_{max} w \quad (4.8)$$

Then, composite weights are computed through the aggregation of the weights within the hierarchy [214]. The global weights of sub-criteria are calculated by multiplying their local weights with that of their upper criterion. Consequently, the sum of the global weights of the sub-criteria within the same cluster is equal to the weight of that criterion [215]. Saaty has shown that λ_{max} is always greater or equal to n (number of rows and columns) [205]. If the pairwise comparisons do not include any inconsistency, $\lambda_{max} = n$ or, in other words, the more consistent the comparisons are, the closer the value of computed λ_{max} is to n. However, it is worth mentioning that "the eigenvector method yields a natural measure of consistency" [214]. In case of high inconsistency, it is usually asked to experts to check and eventually reconsider their judgements [205].

Step 6: Calculating overall priorities Once completed the steps of pairwise comparisons, the judgements of the different stakeholders are combined, allowing the calculation of the overall priorities for the alternatives and their final rankings to reach the scope of the decision process. The AHP method considers an "additive value function to calculate the overall priorities for the alternatives" [215]. In other words, the overall priority is obtained calculating the weighted average of all priorities (i.e. "sum of the priority of this alternative on each criterion multiplied by the weight of the corresponding criterion" [215]). Clearly, alternatives with higher priorities are assumed to be more valuable or more preferred. According to Hummel et al., "the overall priorities can be used to select the most preferred alternative; to rank order the alternatives from most preferred to least preferred; or to determine the relative value of these alternatives" [215].

Study: European grid modelling

Parallelly to the development of the A'WOT approach, this step consists in the identification and development of a power system baseline model, based on an open-source database, and in the analysis of the TYNDP 2018 network plan for the European power system, to evaluate the planned transmission capacity expansion and the projections of the baseline model up to 2030 and 2050.

Moreover, in line with the application at global scale reported in section 4.1, the main techno-economic parameters used as input in the modelling exercise (i.e. LCOEs, electricity generation, installed capacity, load) need to be projected in accordance with the main assumptions of the GEI vision for 2030 and 2050.

Simulate and support: optimization

The optimization algorithm developed in $MATLAB^{®}$ environment has two objective functions [79]:

- minimization of the congestion in the network;
- minimization of the electricity generation costs of the installed generators, under the unified European electricity market assumption.

The following constraints were considered [79]:

- the power balance of the entire network should be guaranteed;
- the model should avoid exceeding the maximum current rating of transmission lines (if possible);
- the distribution of the needed interconnections should be as even as possible;
- the set of interconnector-connected buses in 2030 should be a subset of the one of 2050.

The modelling and optimization steps, even though fundamental for the discussion of the results, were not the main focus of the application. The European network model and the optimization algorithm was developed by Dr. Tao Huang and Zhengyi Han, in the framework of the cited project. The development of the A'WOT methodology and its combination with the power system modelling represents the original contribution of the PhD candidate.

4.2.4 Case study

Goal and decision context framing

A'WOT method was deployed to study the strengths, weaknesses and development trends of electricity interconnections between Europe and its surrounding regions. The work was linked to the GEI vision [32], already discussed in section 4.1, and declined for Europe, dealing with the possible macro-areas to be connected to European countries. The scope of the A'WOT method was to define and rank the European countries most favourable for installing the electricity interconnections among Europe and its neighbouring areas. A simplified representation of the implemented A'WOT method is summarized in Figure 4.14.

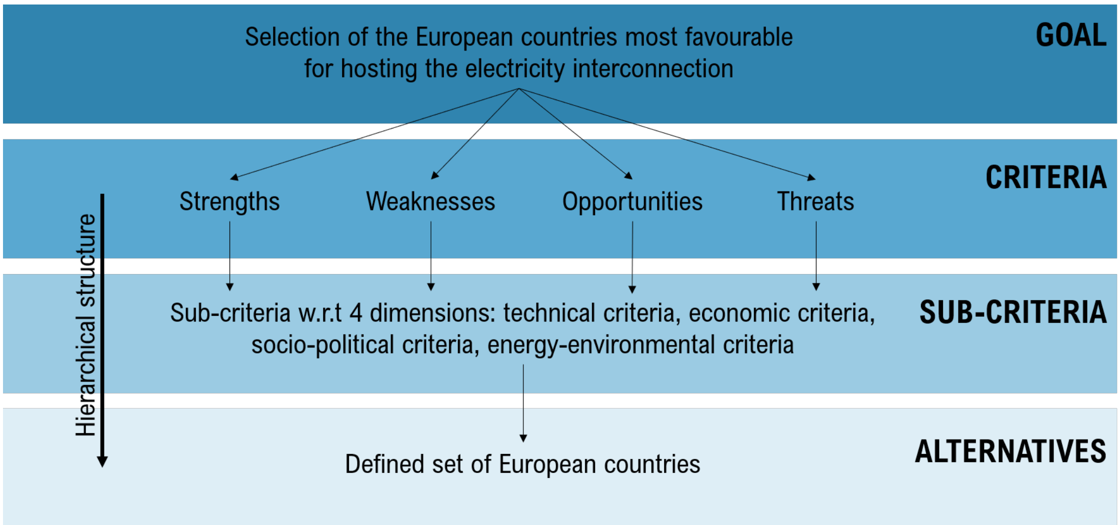
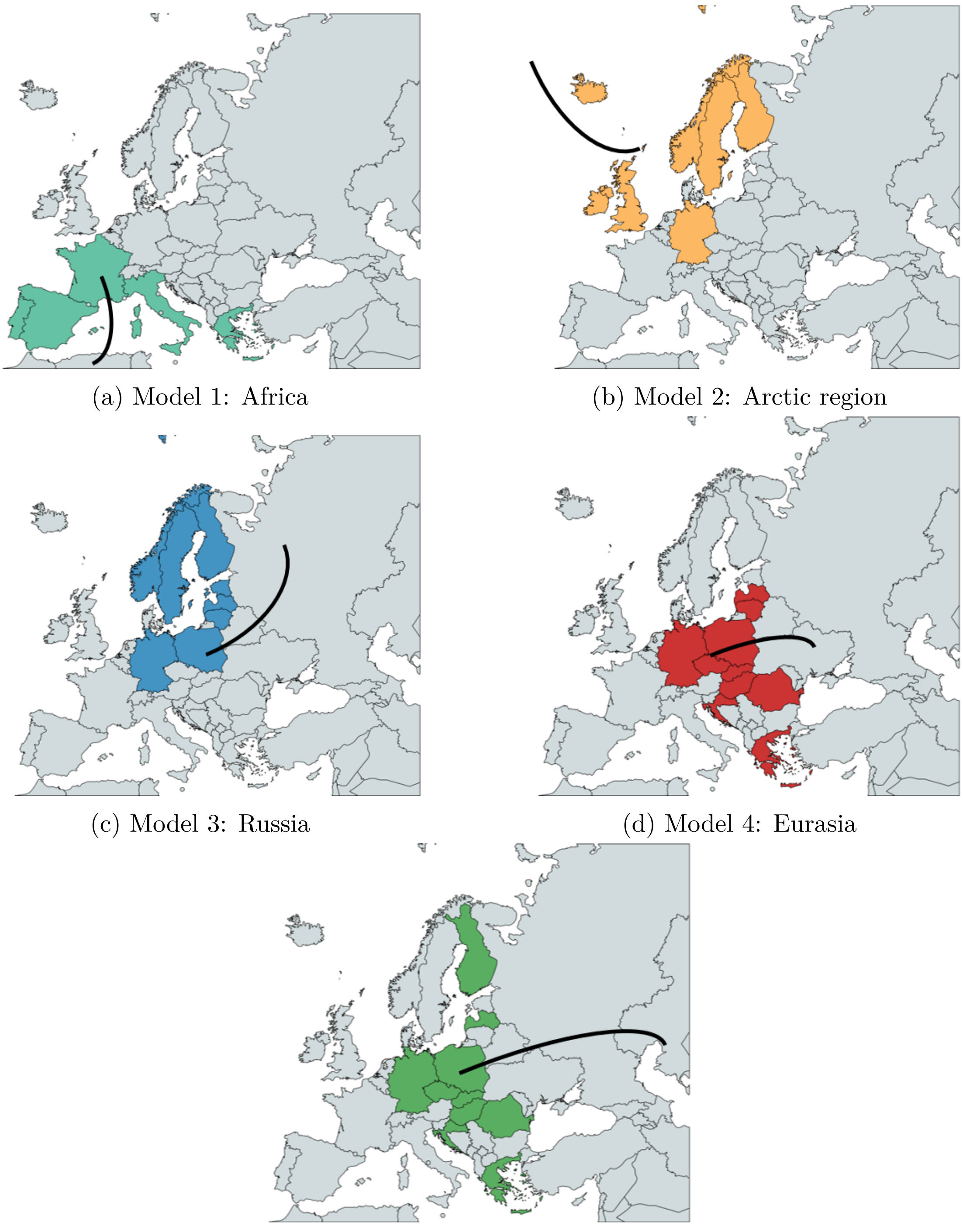


Figure 4.14: Typical structure of hybrid A'WOT method.

Firstly, decision context, goal and alternatives need to be established. Due to the variety of possible interconnections between European countries and the surrounding areas, there was the need to circumscribe the analysis. Therefore, five macro-areas were supposed to be interconnected to European countries, namely China, Russia, Eurasia, Africa and the Arctic region (i.e. Greenland and Barents Sea), the latter being in complete agreement with the GEI vision [32]. The interconnection hypotheses for Europe were derived from the simplified global grid model described in section 4.1, developed assuming the presence of a globally integrated electricity market. For each macro-area to be connected to the European network, an A'WOT model was developed, for a total of 5 models, each representing a different goal for the multi-criteria analysis (i.e. a different interconnection strategy). For each model, alternatives were defined based on the set of European countries that could be potentially connected to each selected surrounding macro-area, identified based on current existing interconnection infrastructure, as well as geographical proximity and political features. A summary of the developed A'WOT models, with the details of goal and alternatives, is presented in Table 4.6 and Figure 4.15. The latter allows to visualize, per each model, the macro-area to be connected (identified with an arrow) and the alternative EU countries defined as potential interconnectors (coloured countries).

Table 4.6: Summary of the developed A'WOT models.

Model	**Goal**	**Alternative**
Model 1	Interconnection between Europe and Africa	France, Greece, Italy, Portugal, Spain
Model 2	Interconnection between Europe and Arctic region	Finland, Germany, Ireland, Sweden, United Kingdom, Iceland, Norway
Model 3	Interconnection between Europe and Russia	Estonia, Finland, Germany, Latvia, Lithuania, Poland, Sweden, Norway
Model 4	Interconnection between Europe and Eurasia	Croatia, Germany, Greece, Hungary, Latvia, Lithuania, Poland, Romania, Slovak Republic
Model 5	Interconnection between Europe and China	Finland, Germany, Greece, Hungary, Latvia, Lithuania, Poland, Romania, Slovak Republic



(a) Model 1: Africa

(b) Model 2: Arctic region

(c) Model 3: Russia

(d) Model 4: Eurasia

(e) Model 5: China

Figure 4.15: Geographical representation of the developed A'WOT models: (a) Africa; (b) Arctic region; (c) Russia; (d) Eurasia; (e) China.

Stakeholders' analysis and criteria definition

Sub-criteria were selected based on the analysis reported in Crespi et al. [88], which summarizes the results of a literature review carried out to identify the interests of the main macro-players potentially involved in the planning process of transmission network expansion, as well the perceived obstacles and barriers for the realization of these projects. As reported in Ref. [88], "*stakeholders' analysis is typically used to explore people or institutions having a significant role in the decisional process. When approaching electricity planning, four categories of stakeholders are usually considered [88]: managers of transmission networks (i.e. transmission administrator, system operator, network owners), users of transmission networks (including consumers and power producers), facilitators of the energy trade (i.e. market operator, energy retailers, energy traders) and authorities (including regulators and public authorities) [217]. In this research, the stakeholders presented in Table 4.7 were considered, specifying their own typical interests for the realization of the large-scale transmission expansion projects.*

Table 4.7: Main stakeholders and their interests in transmission expansion planning [217, 218, 219, 220, 221, 222]. Extracted from Ref. [88].

Stakeholders	**Interests**
European Commission	Creating an Internal Electricity Market, achieving physical and economic integration; achieving main energy policy targets: security of supply, economic efficiency, environmental impacts reduction
National governments	Maximizing social welfare and market efficiency; assuring security of supply, affordability and price reduction for consumers; facilitating renewables integration
Regulators	Encouraging competition; providing equity for all parties seeking network access; balancing TSOs interests with social welfare and costumer interests
Transmission system operators (TSOs)	Facilitating RES integration and development of cross-border connections; providing system stability; finalizing new grid investments; increasing flexibility and network reliability; reducing congestion and transmission losses
Network owners	Minimizing investment costs and maximising revenues
Power producers	Removing transmission constraints for dispatching generators and providing competitive environment; increasing network reliability and flexibility
Bank	Having guaranteed return of investment

It has to be noted that the stakeholders identified in Table 4.7 can be targeted as macro-players, being those motivated by interests that can determine their support or rejection of a strategy, and are mainly driven by economic or financial interests. However, their potential decision is reflected in energy systems transformations, which might affect other categories. In this regard, other micro-players could be identified, as distributed system operators (DSOs), final costumers, or environmentalists, whose perceptions and intents should be considered in the choice of alternative expansion strategies, despite their low power in the decision-making process" [88].

The analysis was performed with the scope of extrapolating the main criteria, based on which the hybrid A'WOT method should be developed. In particular, as reported in Ref. [88], criteria related to market competition and security of supply should be used to reflect the interests and objectives of system operators and governments, while network owners and power producers would be more interested in financial aspects, as investment and operation costs. According to government and regulators interests, criteria of energy affordability and social welfare might be considered, to evaluate the benefits of transmission expansion for the society [88]; environmental issues should be introduced as well [88]. Moreover, as discussed by Crespi et al., "*to ensure the MCDA to describe the decisional context in all its facets, it is interesting to define criteria also addressing its main weaknesses and threats. Transmission expansion planning topic is hemmed in several barriers and obstacles, not just related to technical issues [219]. Indeed, the main perceived barriers for the realization of these projects are lack of harmonized regulatory framework, public opinion opposition (due probably to scarcity of communication and information), length of administrative processes and authorisation procedures, absence of transparency and lack of clear definitions of responsibilities among the main involved stakeholders. For this reason, socio-political criteria have to be included in the analysis, in order to tackle these barriers (e.g. criteria of political stability, government effectiveness, regulatory quality, control of corruption, length of administrative procedures, public acceptance, etc.)*" [88].

Table 4.8 reports the identified criteria, sub-divided into 4 categories, in order to tackle the transmission expansion planning issue under different dimensions (i.e. technical, economic, socio-political and energy-environmental criteria) and to consider the factors that might potentially affect the decision-making process (a brif description of the criteria is presented in Appendix A).

The A'WOT methodology requests the sub-criteria to be organized in the form of the SWOT analysis, dividing them accordingly to their capability of pushing or hindering the projects fulfilment. With the objective of realization of the interconnections, the strategical factors were organized into the common SWOT quadrant chart. Each selected criterion is quantitative, allowing a direct numerical comparison between the different countries. Once identified the set of criteria, these were organized among the four SWOT groups. It is important to note that a single

Table 4.8: Identified criteria for the multi-criteria analysis.

Technical criteria	**Economic criteria**	**Socio-political criteria**	**Energy-environmental criteria**
Electric power transmission losses	Investment in electricity transmission	Political stability	CO_2 emissions
Congestion in national power grid	Inflation	Government effectiveness	Electrical load growth
Existence of interconnection structure	Cost of money (price level index)	Regulatory quality	Current electrification of final uses
Number of smart grid projects	Cost of business start-up procedures	Control of corruption	
Concentration of national wholesale market	Time required to start a business	Presence of subsidies	
	Income inequality (GINI coefficient)	Social acceptance of RES installation	
	Employment rate	Socio-economic energy risk index	
	Electricity prices		

four-quadrant SWOT chart was defined for all five developed A'WOT models, as presented in Figure 4.16, being their identified goals similar.

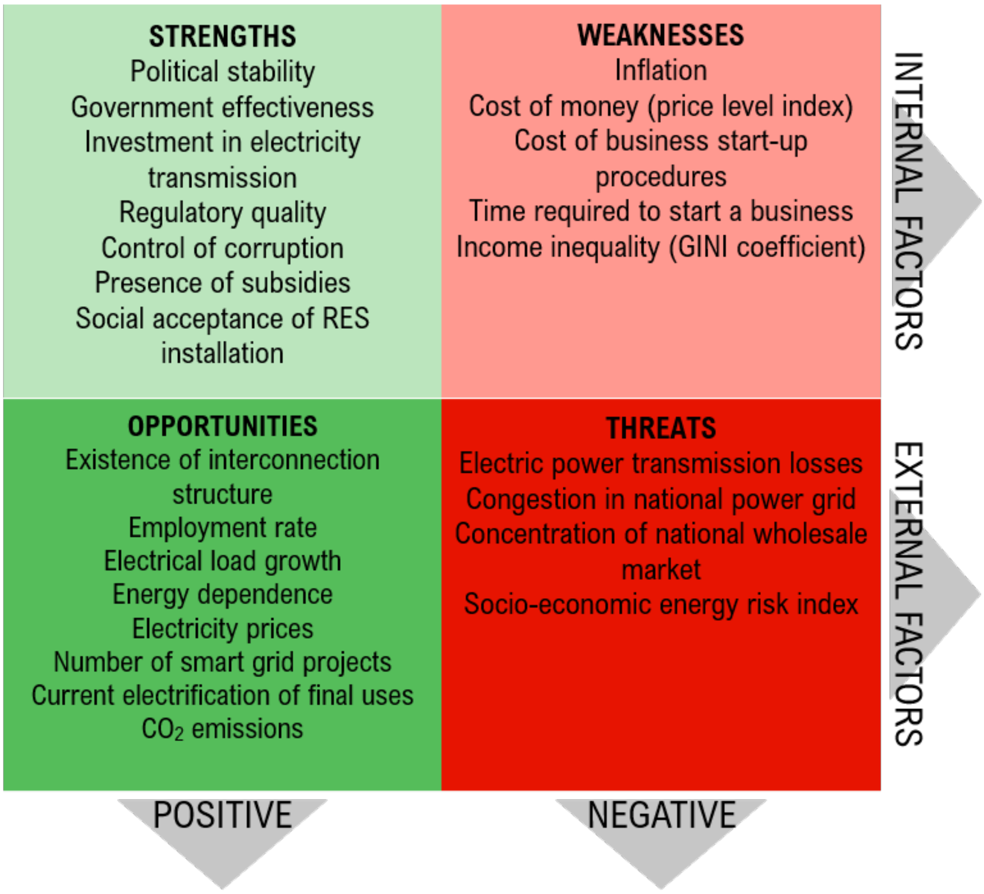


Figure 4.16: SWOT four-quadrant chart for the analysis of electricity interconnections between Europe and its surrounding countries.

Pairwise comparison

For conducting the evaluation procedure, four experts were identified, as representative of different interests and with diverse expertise and background: E1, expert in energy field and modelling; E2, expert in power systems modelling, power system economics and geopolitics; E3, expert in socio-economic field, multi-criteria analysis and decision-making support methods; and E4, expert in power systems modelling and technologies. The format of pairwise comparison was submitted separately to the four experts, between 30^{th} and 31^{st} of October 2018.

The four experts were asked to fill in the pairwise comparison questions, with reference both to SWOT criteria and sub-criteria. It has to be noticed that, being sub-criteria related to specific performance indicators, these were compared only once for all the models, assuming that their importance with respect to the upper criteria would not be affected by the models themselves. Conversely, the SWOT factors (i.e. strengths, opportunities, weaknesses, threats) were compared for each of the considered models, as they can be directly linked to the five macro-regions under investigation.

As far as the sub-criteria level is considered, for the sake of exemplification, the following question specifies the request submitted to the experts for the comparison:

With reference to the upper criterion STRENGHTS, given the sub-criteria POLITICAL STABILITY (PS) and GOVERNMENT EFFECTIVENESS (GE), which element is more important and how much more important is it?

PS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	GE

Table 4.9 presents, for the expert E1, an example of comparison matrix of the SWOT factors, with respect to their relative SWOT group (strengths), and the obtained local priorities of the factors within the group, while Table 4.10 reports the local priorities of the sub-criteria (SWOT factors) with respect to the four upper criteria.

Table 4.9: Pairwise comparison matrix of the sub-criteria with respect to the "strengths" criterion (expert E1).

	PS	GE	IET	RQ	CC	PS	SARI	**Local priorities of the factor within the group**
Political stability (PS)	1	6	1/7	1/6	4	1/5	5	0.168
Government effectiveness (GE)	1/6	1	1/8	1/8	1/7	1/8	1/2	0.103
Investments in electricity transmission (IET)	7	8	1	8	6	6	9	0.225
Regulatory quality (RQ)	6	8	1/8	1	6	1/7	7	0.103
Control of corruption (CC)	1/4	7	1/6	1/6	1	1/5	7	0.104
Presence of subsidies (PS)	5	8	1/6	7	5	1	8	0.206
Social acceptance in RES installation (SARI)	1/5	2	1/9	1/7	1/7	1/8	1	0.091

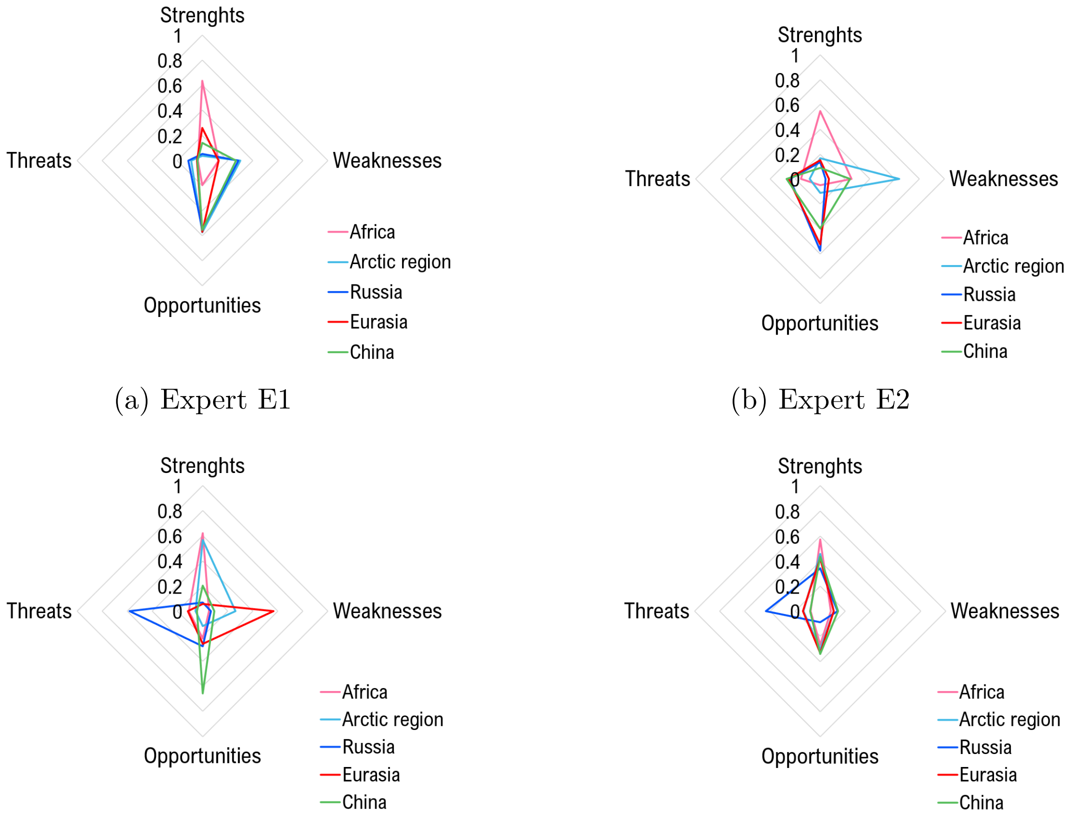
According to E1's preferences, among the set of sub-criteria belonging to the strengths criterion, "investments in electricity transmission" (0.225) and "presence

Table 4.10: Local priorities of sub-criteria (SWOT factors) with respect to their relative upper criteria (expert E1).

Criteria (SWOT groups)	**Sub-criteria (SWOT factors)**	**Local priorities of the factor within the group**
STRENGTHS	Political stability	0.168
	Government effectiveness	0.103
	Investments in electricity transmission	0.225
	Regulatory quality	0.103
	Control of corruption	0.104
	Presence of subsidies	0.206
	Social acceptance in RES installation	0.091
WEAKNESSES	Inflation	0.073
	Cost of money	0.208
	Cost of business start-up procedures	0.138
	Time required to start a business	0.342
	GINI coefficient	0.238
OPPORTUNITIES	Existence of interconnection structure	0.153
	Employment rate	0.063
	Electrical load growth	0.130
	Energy dependence	0.242
	Electricity prices	0.150
	Smart grid projects	0.034
	Current electrification of final uses	0.080
	CO_2 emissions	0.149
THREATS	Electric power transmission losses	0.095
	Congestion in internal grid	0.422
	HHI in electricity market	0.243
	Socio-economic energy risk index	0.240

of subsidies" (0.206) are those with the highest importance, followed by "political stability" (0.168). As for weaknesses, the item "time required to start a business" seems to be the most important element, even though the socio-economic condition of the countries, expressed through "GINI coefficient" and "cost of money" sub-criteria, represents a significant aspect to consider. "Energy dependence" and "CO_2 emissions", among opportunities, appear to be the most preferred items (0.242 and 0.149, respectively); indeed, interconnections should allow to transfer clean energy to meet electricity demands, representing a promising option for reducing countries dependence on fossil fuels and GHG emissions. Also, the "existence of interconnection structure" is considered as a relevant opportunity, meaning that the country with existing infrastructure might be favoured in hosting future interconnection plans. Finally, as for threats, "congestion in internal grid" is considered the most significant sub-criterion (0.422). Following a similar procedure, also other experts were interviewed, thus allowing to score the sub-criteria according to their preferences.

Regarding criteria, as previously anticipated, they were compared by the experts separately per each of the five models defined before, to tailor their preferences between the SWOT groups with respect to the goals of the different models. Figure 4.17 graphically represents the individual experts' preferences of the SWOT groups for each A'WOT model.



(a) Expert E1

(b) Expert E2

(c) Expert E3

(d) Expert E4

Figure 4.17: Individual preferences of the SWOT groups for each A'WOT model for the four selected experts.

As it is possible to see from Figure 4.17, for all experts, strengths obtained the highest score for the Africa model, expressing the high potential that the exploitation of interconnections with Africa could represent for the European energy system. Regarding the Arctic region, the experts have diverse opinions; indeed, if

E1 assigned the highest score to opportunities, this interconnection obtained the highest ranking for strengths for E3 and E4 and for weaknesses for E2. This controversial situation is most likely associated to the specific governance situation of this region, which will need strong global cooperation in order to be efficiently managed and deployed. As for the other models, E1 positively judged all interconnection strategies, giving the highest scores to opportunities for Russia, Eurasia and China. The same judgements were provided by E2, while for E3 and E4 different behaviours can be observed. Indeed, E3 assigned the highest score to threats for the connection with Russia, probably due to the geopolitical tensions observed in recent years, and to weaknesses for the connection with Eurasia, while the judgement for China is coherent with those of E1 and E2. E4 identified strengths as the highest criterion for all models, with the sole exception of Russia, for which E4 highly judged threats.

Finally, pairwise comparison needs to be performed for comparing the alternatives with respect to each sub-criterion, for each model. Since the sub-criteria selected in the SWOT analysis were all quantitative, this step was performed without the experts' participation. Sub-criteria were normalized using a mode ideal normalization, according to Eq. 4.9 [216]:

$$V_{normalized} = \frac{V_{actual}}{V_{maximum}} \tag{4.9}$$

In this way, the quantitative values of the sub-criteria were normalized on a 0-1 scale. The normalized scores, per each alternative and sub-criterion, were then translated into a 1- to 9-scale (in line with Saaty's fundamental scale, Table 4.5). The differences between the obtained scores represents the judgements to be used for the related pairwise comparisons of the different alternatives according to each sub-criterion [216].

European grid modelling

Moving to the modelling objective, the European network was modelled starting from the open-source model developed by Hörsch et al. [223], as reported in Ref. [79] (see Figure 4.18). The model, composed by 257 buses, presents the useful level of detail in terms of geographical coverage and grid connectivity in order to take into account the possible interconnections from diverse directions [79]. Based on the latest TYNDP [199], it was possible to extract information on the AC and DC lines planned for 2030 and 2050, which were introduced into the baseline model (please refer to Ref. [79] for more details).

GEI scenario

In line with the assumptions for the global scale application described in section 4.1, European electricity figures were projected for 2030 and 2050, in accordance

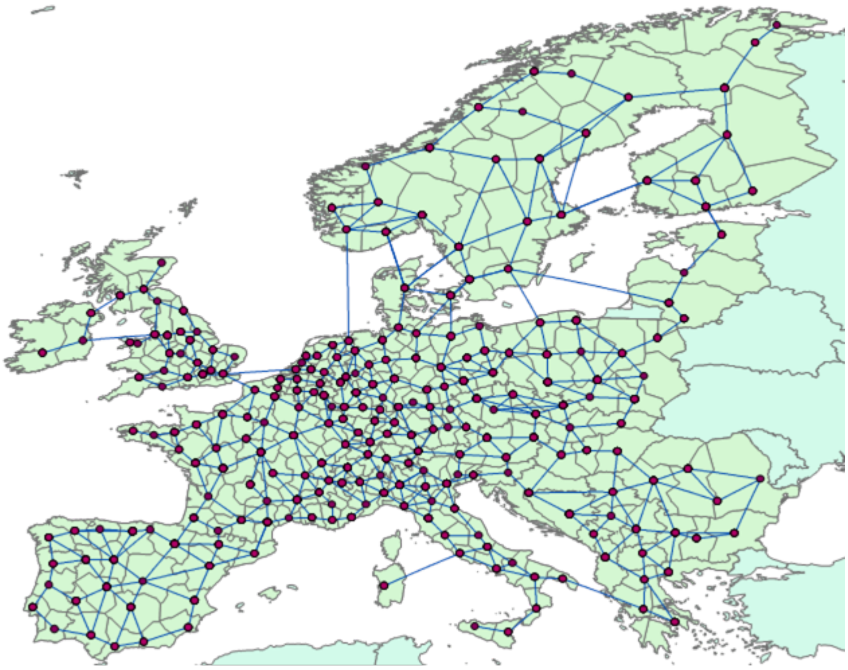


Figure 4.18: Simplified 257-buses European network [6].

with the GEI vision. Based on Liu's forecasts [32], information on the installed renewables capacities in Arctic and Equatorial regions were gathered, together with figures on the load growths projections.

Furthermore, power corridors were defined and characterized to connect the European network with surrounding areas (i.e. Arctic region, Russia, China, Eurasia, and Africa) and the capacity requirements of these corridors were derived from the outcomes of the global analysis reported in section 4.1. Despite the different spatial granularity of the European application, the capacity values obtained in the previous application were assumed still valid. The values are summarized in Table 4.11, together with the estimation of the numbers of interconnectors needed, assuming for all the interconnections the +/-1100 kV CSC-HVDC technology.

All European countries were characterized in terms of load, installed capacity and LCOE data. Hourly load profiles derived from ENTSO-E platform [224] were projected adopting the growth rates derived from Liu's forecasts. As for the generation side, the existing conventional generators already present in the considered European baseline network were updated. In line with the previous analysis, LCOE was used as economic indicator for defining the generators cost curves. Due to the high LCOE values characteristics of Europe, the GEI scenario assumes that the increment of the local electric demand would primarily rely on the renewables installed in the neighbouring regions, while the European installations would still be in line with the actual official plans. To project the electricity generation mix for

Table 4.11: Intercontinental power corridors: capacities and numbers of interconnectors in demand for 2030 and 2050.

Connected area	**2030**		**2050**	
	Capacity [GW]	Lines	Capacity[GW]	Lines
Africa	220	19	730	61
Arctic region	90	7	280	25
Russia	120	9	460	39
Eurasia	110	10	110	10
China	200	16	260	22

2030 and 2050, the growth rates assumed in the "Current Policy" scenario from WEO 2016 [181] were considered.

4.2.5 Key findings and discussion

Outcomes from A'WOT development

All the computations and score aggregations were performed with the help of the Expert Choice software [225], which is particularly suitable for organizing the decision context, collecting experts' answers and joining the individual preferences of all the involved experts. The combined preferences for the five models are reported in Table 4.12.

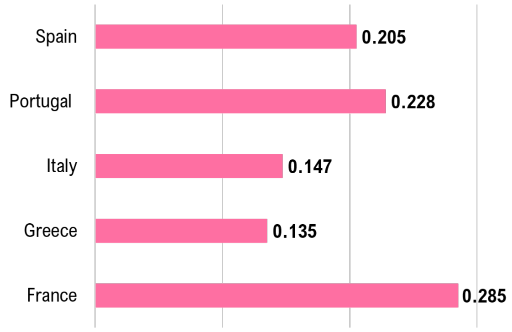
Table 4.12: Combined priorities of the SWOT groups per each of the developed A'WOT models.

Criteria	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model 5**
Strengths	**0.628**	0.255	0.142	0.208	0.205
Weaknesses	0.116	**0.353**	0.131	0.182	0.192
Opportunities	0.166	0.282	**0.370**	**0.474**	**0.517**
Threats	0.089	0.110	0.357	0.137	0.086

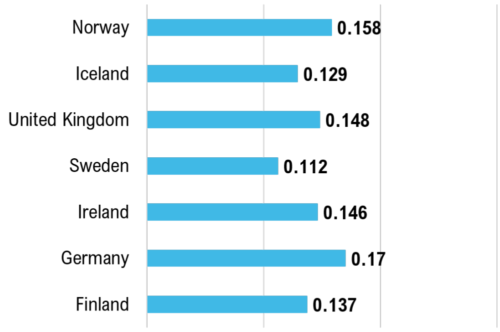
From Table 4.12, it is possible to observe the differences among the five models. Strengths obtained the highest preference for model 1 (Africa), meaning that countries with higher values for strengths criteria would be preferred to the other alternatives. Africa load is expected to grow substantially in the following years, and for this reason, this interconnection clearly represents a chance, as suggested by the several initiatives in this direction [32, 80, 191]. This is true especially from a social point of view, since interconnections could also provide higher access to electricity to African countries. Furthermore, from the European point of view, the exploitation of African high potential for solar production can have a crucial role in the low-carbon transition. A different result was obtained for the Arctic region, for which weaknesses appeared to be the most concerned criterion. The main explanation for this combined ranking might be related to the authority issues arising when considering the installation of wind power plants in this region. Indeed, despite the promising renewable potential of this area, still regulatory quality, as well as political agreements in terms of sovereignty, investment allocation and financing efforts are missing [26]. Opportunities and threats obtained the highest rankings for the Russian connections (model 3). This could be a result of the current situation, in which Russia represents, on one side, one of the main energy exporters for Europe (mainly of fossil fuels), while, on the other side, it represents a challenge, due to the actual geopolitical tensions, which in turn are reflected into the issue of security of energy supply, which represents one of the major concerns nowadays in Europe [226]. Finally, models 4 and 5 (Eurasia and China, respectively) are characterized by the highest relevance of opportunities. This situation is probably linked to the high renewable energy potential in Asia (in terms of hydro, wind and solar), that might help Europe in reducing its fossil fuel dependence on other countries. These results are probably linked also to the Belt and Road Initiative (BRI) framework, promoted in the last years by the Chinese government, aiming to create higher trade connectivity with European countries [227] and to enhance a stronger EU-Asia cooperation, as already demonstrated by the policy agreements already in place (e.g. European Union and China 2020 Agenda for Cooperation [228]). A deepening on this topic was addressed by the PhD candidate in Ref. [22], in which BRI was tackled in energy terms, underlining the black (fossil) and green (RES) trade-off for Chinese investments and technological development. Focusing on China, Table 4.12 shows that strengths and weaknesses are evaluated as similarly important by the interviewed experts, probably related to the high potential for renewable energy deployment in China from one side, and the political stability and international cooperation framework on the other side.

Once filled the complete set of comparison matrices, through Expert Choice software, it was possible to calculate the overall priorities of the alternatives per each model. As mentioned before, these rankings define the countries most suitable for hosting the projects of intercontinental electricity interconnections for connecting European countries to the five selected macro-areas, based on a multi-dimensional approach. By integrating different aspects (i.e. economic, technical, social and political), it was possible to rank the considered alternative countries and to eventually choose among them for the future development of the grid. The overall priorities are presented in Figure 4.19.

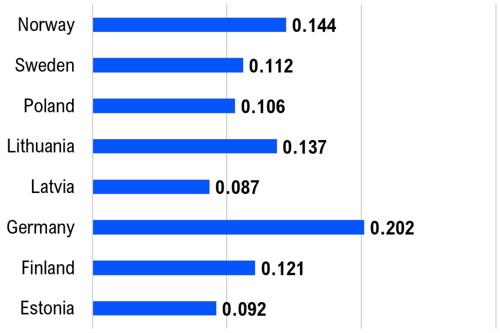
Starting from model 1 (Africa), it is possible to observe that the A'WOT model sets France as the most preferred country (with an overall score of 0.285), followed by Portugal (0.228) and Spain (0.205). Greece ranks in the last position, most probably penalized by its recent political instability. France is preferred to other competing countries, since it is characterized by very high values for the sub-criteria



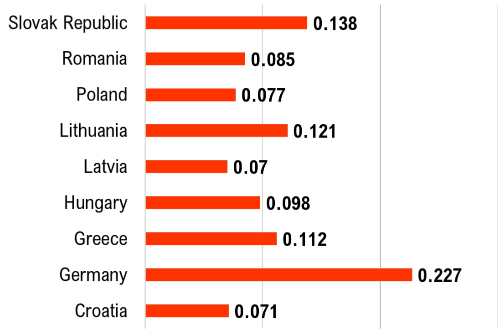
(a) Model 1: Africa



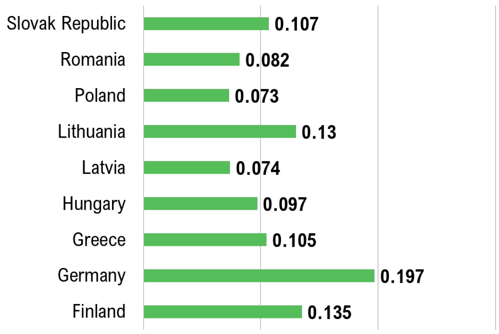
(b) Model 2: Arctic region



(c) Model 3: Russia



(d) Model 4: Eurasia

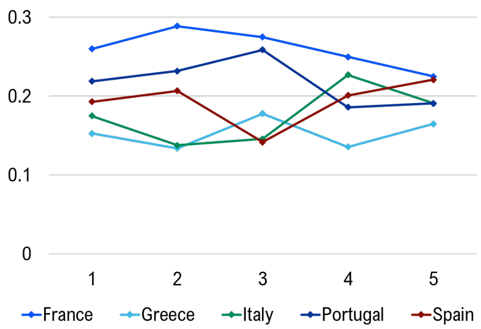


(e) Model 5: China

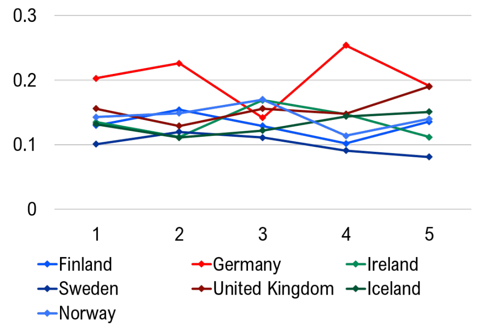
Figure 4.19: Overall ranking of alternatives for different models: (a) Africa; (b) Arctic region; (c) Russia; (d) Eurasia; (e) China.

ranked as strengths and opportunities, in turn defined as the most relevant by the experts, when considering the interconnection from Africa. In the case of connection with the Arctic region, the best performing countries are the ones able to minimize the weaknesses and, in parallel, to strengthen the opportunities, as reported in Table 4.12. Germany appears to be the best country for this interconnection (with an overall score of 0.170), closely followed by Norway (0.158). Sweden is in the last position, with a value of 0.112. Germany is the country with the highest electricity investments programmed up to 2030, as well as the highest number of smart grid projects, planned or ongoing. However, for the other criteria, the distance among the countries is not highly significant and this explains why other countries can compete with Germany. As for model 3 (Russia), Germany appears to be the best performing country (with an overall score of 0.202), with a significant gap with the other alternative options. Norway (0.144), Lithuania (0.137) and Finland (0.121) present fairly good results, while Latvia represents the worst solution for the interconnection. A similar consideration is valid for models 4 and 5. Regarding the interconnection with Eurasia, Germany ranks first (0.227), with a gap with other alternatives even more exacerbated than in model 3. Here, many countries appear to obtain similar low scores: Romania (0.085), Poland (0.077), Croatia (0.071) and again Latvia (0.070). As for China (model 5), the overall rankings highlight that Germany has achieved excellent scores also in this model, with a score of 0.197, while Latvia (0.074) and Poland (0.073) presents the worst results. The possible explanation has to be found in the higher discrepancies between Germany and the other alternatives, especially Romania, Poland, Hungary and Latvia, due to the bad situations of those countries with respect to the opportunities criteria, which are accounted as the most preferred ones by the stakeholders for this model (Table 4.12).

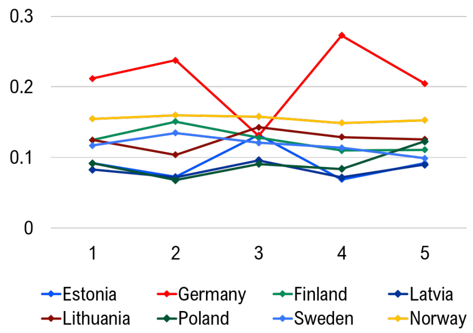
To test the stability of the results, sensitivity analyses were performed, using the "one at a time" approach. Per each of the five models, priorities of the criteria were separately varied, considering five cases: 1) 25% equal weights to strengths, weaknesses, opportunities, and threats; 2) 70% weight to strengths criterion and 10% to the other criteria; 3) 70% weight to weaknesses and 10% to the other criteria; 4) 70% weight to opportunities and 10% to the other criteria; 5) 70% weight to threats and 10% to the other criteria. The changes in the overall rankings are presented in Figure 4.20, where the numbers on the x-axis represents the five sensitivity cases. In the first model, it is clear that there are no changes in the overall ranking of priorities, since France always stands over the other alternatives. For the other models, only for the case 3 (when a weight of 70% is fixed to the weaknesses criterion) there is a change in the ranking. Since for all the other cases Germany appears to have the highest ranking, in accordance with the results of the models, it is possible to state that for all the models the results are stable for all models. To conclude, as it is possible to note from Figure 4.19 and further consolidated by the results of the sensitivity analyses (Figure 4.20), Germany appears to be the best solution for hosting electricity interconnections in all the models where it was accounted as an alternative (model 2, 3, 4 and 5). The different models were separately assessed and for this reason, despite the concurrent presence of similar countries in more than one model, it was not possible to make comparisons and evaluations between them. Specifically, it was not possible to make a direct comparison between the rankings and the scores that Germany obtained. The AHP model itself does not consider any dependencies among the different factors in the model, which can instead be the case. Indeed, even though not performed in this application, further work needs to be devoted to the comparison of the five models, to better describe Germany behaviour.



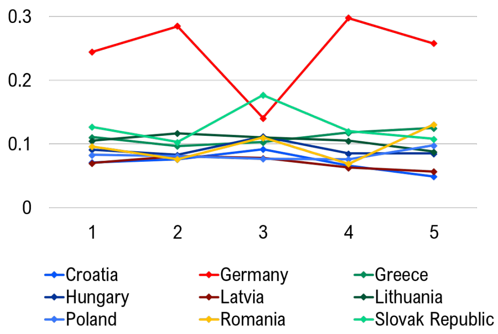
(a) MODEL 1



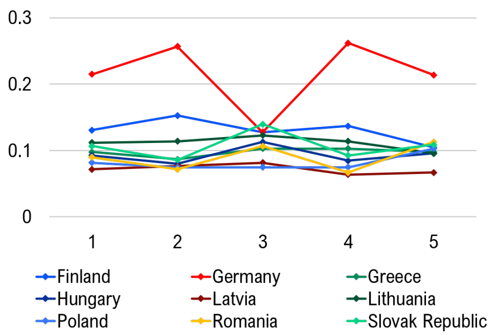
(b) MODEL 2



(c) MODEL 3



(d) MODEL 4



(e) MODEL 5

Figure 4.20: Overall ranking of alternatives for different models according to different sensitivity analyses: (a) Africa; (b) Arctic region; (c) Russia; (d) Eurasia; (e) China.

European grid modelling

Thanks to the application of the hybrid A'WOT method, it was possible to score and rank, for each neighbouring area to be connected to Europe (i.e. Africa, Arctic region, Russia, Eurasia and China), the countries candidate to potentially host interconnections. Specifically, the total number of intercontinental power corridors in demand for 2030 and 2050 (as summarized in Table 4.11) per each macro-area were subdivided among the candidate countries, on the basis of their rankings from the outcomes of the A'WOT application. Figure 4.21 and Figure 4.22 show the amount of interconnectors to be connected to the five geographical zones and their distribution among the candidate countries, for 2030 and 2050, respectively. The highest variations between 2030 and 2050 are experienced in Africa and in the Arctic region, being the zones most affected by the forecasting of RES installations according to the GEI scenario.

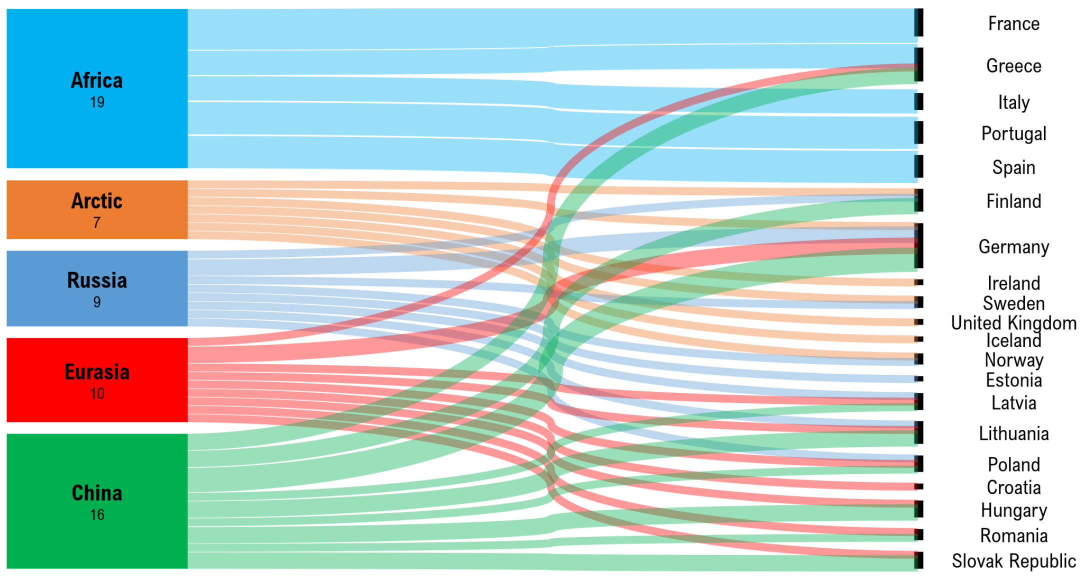


Figure 4.21: Intercontinental power corridors and their landing countries for 2030.

Once evaluated the number of power corridors to be installed in each European country, the multi-objective optimization was run for 2030 and 2050, in order to identify the proper accessing nodes in each national grid. Aiming to set up the network interconnection scheme, the optimization is run for the peak load hour. Since the results of the previous application contain 24 hours power loads in the intercontinental corridors, it was necessary to select the power flows at the exact hour in which the European model is at its peak load. To this purpose, it was assumed that at the peak of local load, Europe would import the most electricity from outside; therefore, the peak hour for the optimization procedure was chosen

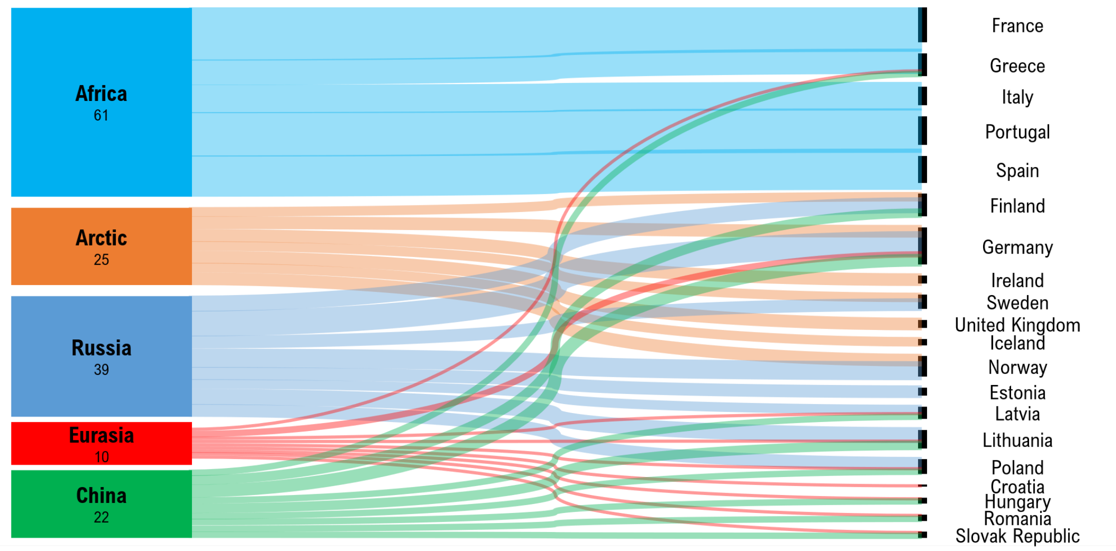


Figure 4.22: Intercontinental power corridors and their landing countries for 2050.

comparing the total imported power flows from outside Europe (according to the results of the global application of section 4.1) and selecting the hour with the maximum import [79].

The simulation step was developed in order to estimate the power flow distributions in the European network for both 2030 and 2050, under the premises of the GEI scenario, and to evaluate the eventual needed future updates of the current development plan of the European transmission grid (from TYNDP 2018 [199]), in line with the GEI scenario projections. It should be noted that when applying the optimization to the adopted 257 bus systems, the needed interconnectors appeared to be higher than the available buses in some countries. Therefore, prior to the optimization step, it was necessary to adjust the numbers of interconnections, in order to avoid network violation and mismatching between the buses of the EU countries. Specifically, some interconnectors in some countries were pre-merged, in order to use a single bus for all the interconnections from the same geographical area and to distribute the needed capacities from the different areas as evenly as possible. The simulated power flow distribution within the European network for 2030 is depicted in Figure 4.23. Each line has a width representing its capacity, while its colour is used to indicate the congestion.

High levels of congestion are measured in the northern Europe, and more precisely in the Scandinavian area; similar considerations can be done for the interconnectors between Norway and Germany, Sweden and Lithuania, and Lithuania and Poland. These results are linked to the interconnections from Russia, China and Greenland (Arctic region), since the connection of the Scandinavian network was not designed to transfer extra energy from other geographical regions. Therefore,

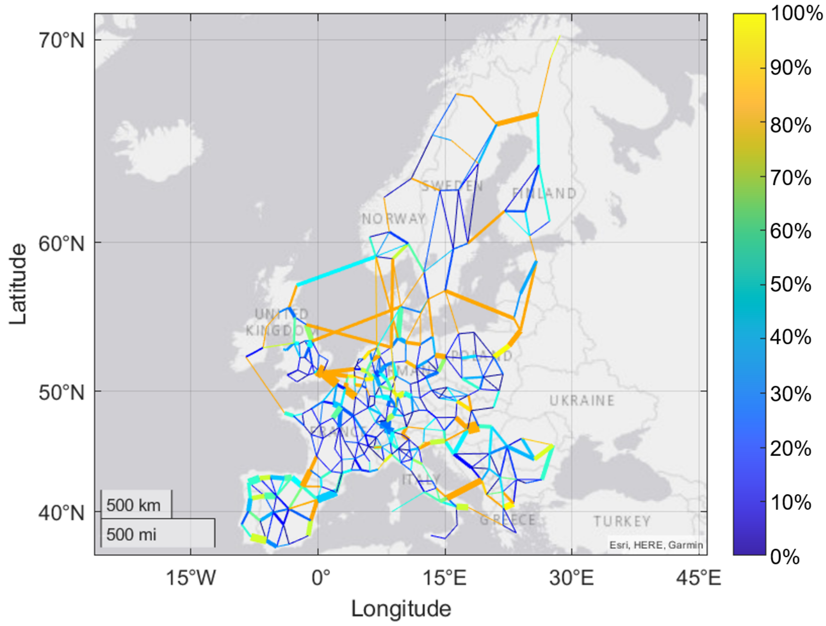


Figure 4.23: Power flow distribution and congestion assessment for the GEI scenario in 2030.

this preliminary simulation shows that, in case the intercontinental power corridors from these regions would be allocated to the Scandinavian countries, the internal interconnections will ask for reinforcement [79]. The situation in central Europe is more stable, with lower stresses on the network. It is worth noting the congestion of the interconnections with United Kingdom. Finally, going South, a moderate stress is visible, even though some problems are experienced, mainly in the connections between Italy and Montenegro. High congestion levels are also experienced in the interconnection between Spain and France, and in the Northern part of Spain, and this condition is coherent with the current weaknesses of the France-Spain cross-border interconnection [79].

In Figure 4.24, the total generation at national level is represented, showing how in the peak load hour, interconnections are deployed, thus reducing the local generation needed. Higher generations are measured in France, Germany and United Kingdom, while moderate generation levels are reported in Austria, Italy, Spain, Sweden and Netherlands. Moreover, analysing the GHG emissions associated to combustible fuel usage, in the 2030 timespan, a total of approximately 5000 $t_{CO_{2eq}}$ is computed for the peak hour, meaning that most activated generators are RES-fuelled. CO_{2eq} emission factors are gathered from Ref. [229], using those estimated through a Life-Cycle Assessment (LCA) approach. Figure 4.25 shows the reciprocal positioning of the European countries in terms of GHG emissions (x-axis) and generation costs (y-axis), the latter calculated multiplying the generation quantities by the respective LCOEs.

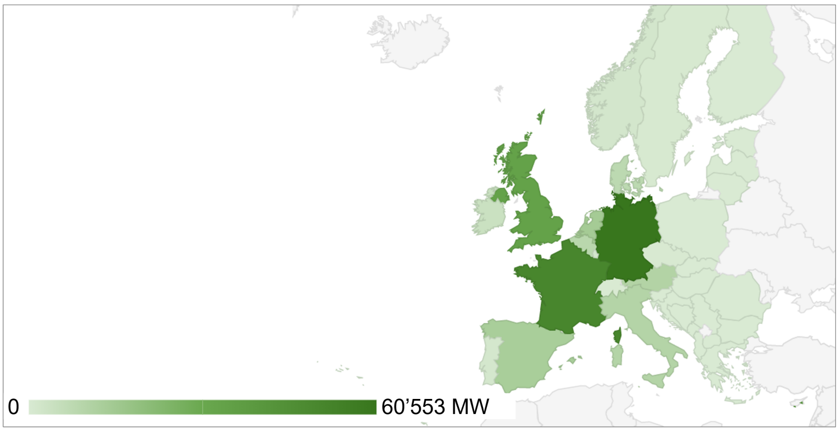


Figure 4.24: National electricity generation in 2030.

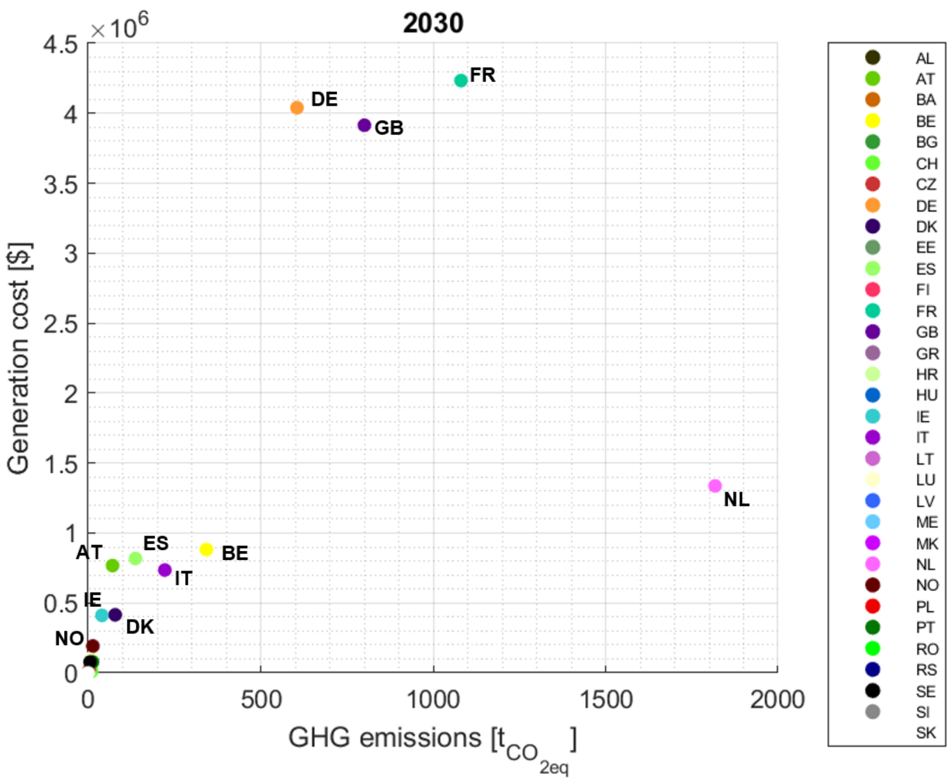


Figure 4.25: National performances in environmental and economic terms in 2050.

Similar considerations are drawn for 2050. Figure 4.26 shows the congestion situation in the European network for the peak hour. Situation has worsened with respect to 2030 results, especially regarding the interconnectors between the Scandinavian area and the European continent, as a consequence of the interconnections from Russia, China and Arctic region. The results for this zone for both time horizons allow to highlight the challenges for the Scandinavian zone network to fully dispatch the wind power resources from the Arctic and the Nordic Sea, under an hypothetical GEI-based scenario [79]. Higher congestion is experienced also in the United Kingdom, and in its connections with France and Germany. Finally, also in the Southern part of Europe, the situation generally worsens, accentuating the congestion problems already measured in 2030; in particular, the worsening of Portuguese and Greek network conditions are related to the higher connections with Africa.

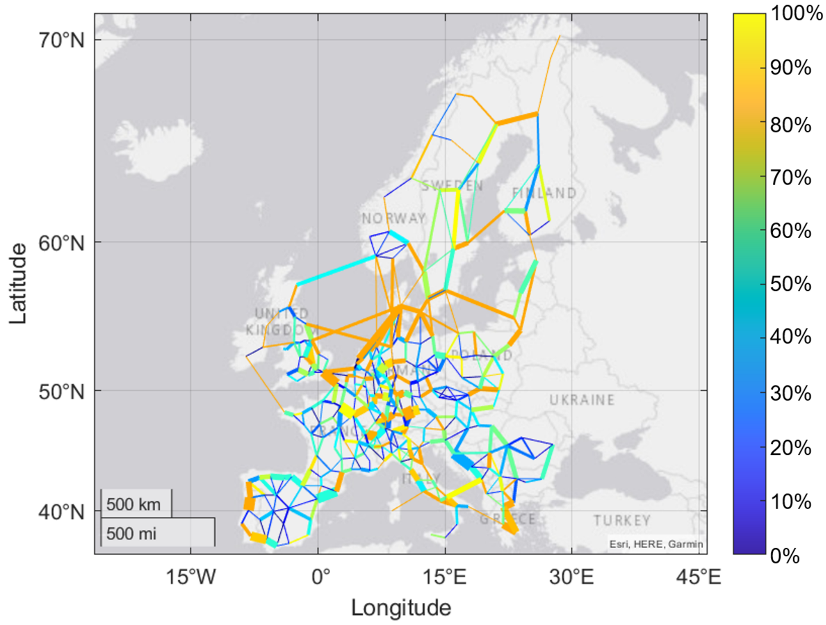


Figure 4.26: Power flow distribution and congestion assessment for the GEI scenario in 2030.

Electricity generation results are reported in Figure 4.27. In the 2050 timespan, a total of approximately 50000 $t_{CO_{2eq}}$ is obtained for the peak hour, highlighting how the demanding conditions of 2050 ask for more generators to be activated and, thus, increasing the overall environmental impact. Similarly to 2030, Figure 4.28 shows the reciprocal positioning of the European countries in terms of GHG emissions (x-axis) and generation costs (y-axis).

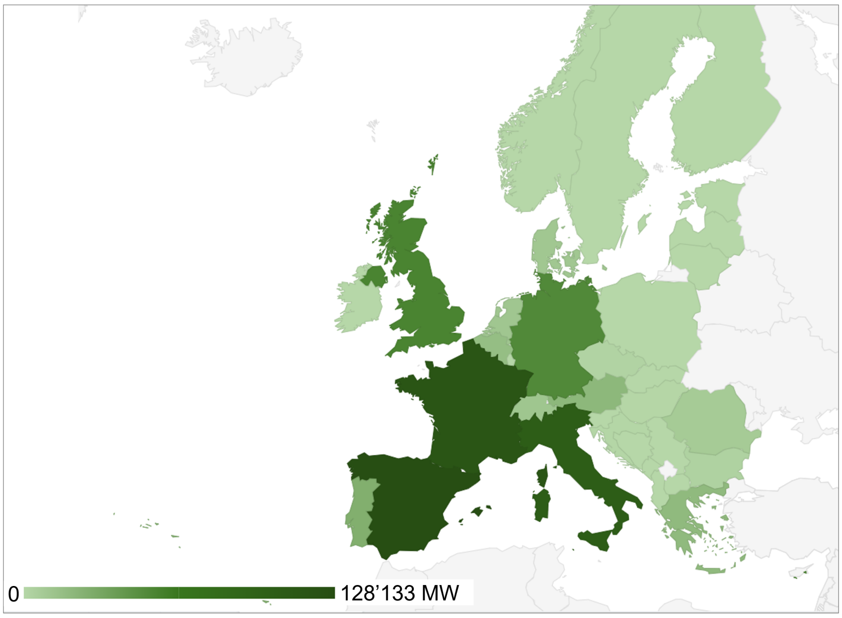


Figure 4.27: National electricity generation in 2050.

4.2.6 Conclusions and further investigation

GEI has been proposed as a possible solution for the achievement of global decarbonization needs. However, while widely deploying renewable energy sources, GEI inevitably sets new challenges to regional and national power grids, by influencing their internal power flow distribution. However, even though traditional power system models are based on purely techno-economic variables, the transition framework asks for more multi-dimensional techniques and methodological framework for approaching energy-policy decision making, helping to combine different dimensions and criteria, stakeholders' objectives and interests.

This application intended to strengthen this need, introducing an innovative methodological approach able to combine traditional expansion planning techniques with socio-economic considerations, thanks to the use of the multi-criteria analysis (in the form of the hybrid A'WOT approach) as input to the step of power system modelling. Specifically, the hybrid A'WOT method was applied to identify the set of European countries most favourable for hosting electricity interconnection projects with the main neighbouring areas (Africa, Arctic region, Russia, Eurasia, China), in line with the GEI vision [32], while their optimal allocation in the European grid was defined through an optimization approach.

The work allowed to evaluate the possible key criteria for the scope of planning and building long-distance electricity interconnections between Europe and its surrounding countries and to rank the most appropriate strategies for EU intercontinental interconnections, highlighting opportunities and obstacles that can

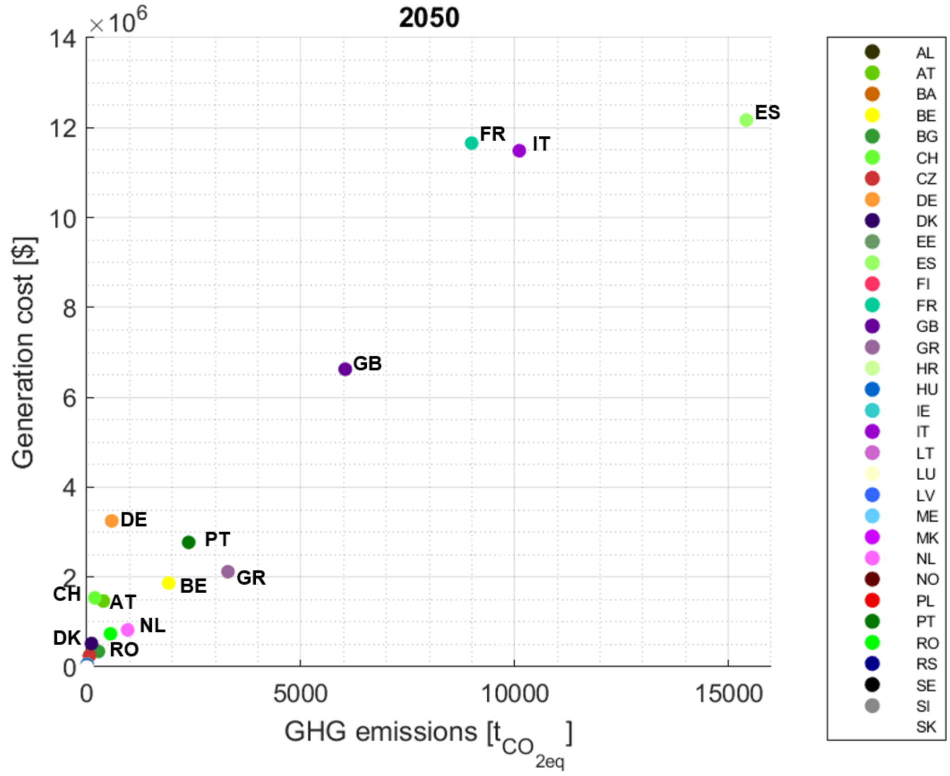


Figure 4.28: National performances in environmental and economic terms in 2050.

arise, based on the description of all strategic factors, either favourable or not, to their realization. High-level and national-based criteria were introduced to create a large-scale decision-making tool, to be potentially used at different international scales, combining different strategic factors, belonging to multiple domains (technical, social, economic, political). Through the development of the A'WOT method, it was possible to profile and compare different European countries with the final goal of defining the best strategies of interconnection. The method, coupling the pure SWOT analysis with the AHP multi-criteria method, allowed to snapshot the decision context, depicting its strengths, weaknesses, opportunities and threats, through the SWOT analysis, and to use the AHP to structure the decision context, involve interested stakeholders and rank the identified alternatives, making the SWOT elements commensurable and performing a study based on quantitative data. For these reasons, the A'WOT method appeared to be a powerful decision-support tool allowing the direct comparison of different strategies, considering criteria and factors belonging to different layers of analysis and creating a ranking of these elements according to experts' preferences.

This requirement is of fundamental importance when dealing with energy transition scenarios. Energy systems affected by current transitions should be defined more appropriately as socio-technical systems, meaning "interconnected, integrated systems that link social, economic and political dynamics to the design and operation of technological systems" [15]. In this framework, energy policy is decisive. Miller et al. reviewed the current goal of energy policy, which nowadays focus on three fundamental aspects: generation and demand matching; minimization of energy cost; reduction of environmental impacts [15]. From this definition, it clearly appears that no social or political aspects are treated and, also, it seems to be assumed that energy systems cannot impact social or political spheres [15]. On the contrary, these elements are of crucial importance when dealing with energy issues. The application of the A'WOT method to the case study of large-scale electricity interconnections highlighted this concept. From the analysis, indeed, it appeared that investments in electricity systems, political stability and regulatory quality are key elements to deal with in the case of planning of large-scale electricity infrastructure expansion, on the same level of purely techno-economic criteria, as the current existence of infrastructure or the investment costs needed for reaching the EU interconnection target. In particular, high political stability and the presence of appropriate regulatory framework represented clear incentives for stakeholders for preferring one alternative over another, as well as the economic availability for electricity systems construction. Moreover, socio-economic issues, as the economic inequality or the presence of subsidies, were accounted as important. It is also worth mentioning that environmental issues were considered significant by the experts, who accounted CO_2 emissions as relevant, identifying their local reduction through the implementation of projects of RES-based interconnected systems as an opportunity.

This result clarifies the need for multi-disciplinary approaches in decision-making processes, demanding to energy policy makers to define strategies able to meet multiple objectives at once. This is especially true when considering complex multi-dimensional sets of objectives, as in case of energy issues, where it might be difficult to compare and assess different strategic solutions or scenarios. Based on the results obtained from this application of the A'WOT methodology and starting from the fact that the AHP model does not consider any dependencies among the different factors in the model, future work will be devoted to the application and test of other multi-criteria tools, among which the Analytic Network Process (ANP) can be mentioned, which permits to explore the interdependencies among the different criteria, thus allowing to better represent the reality and complexity of energy systems. Future work will be developed to review and introduce new indicators and criteria, to better explore the observed Germany behaviour, and thus to better differentiate the final alternative priorities, and to consequently obtain clearer results for the decision-maker. Moreover, geographical or location-dependent criteria are requested, in order to estimate also other environmental impacts related to the realization of the transmission expansion projects, besides the traditional GHG emissions.

Furthermore, the modelling exercise allowed to highlight how GEI will set new challenges to regional power grids, by changing their internal power flow distribution, and asking for further work to study the compatibility of local power grids with an hypothetical GEI vision in the medium- and long-term. The application allowed also to demonstrate that the planning of GEI will require close and strong coordination between TSOs and institutions at international and national scales, in order to successfully put in place this ambitious power grid paradigm.

To conclude, the work contributed to demonstrate how evaluation tools are powerful instruments for approaching energy policy decision-making, combining different dimensions, objectives and interests. In particular, the application of the hybrid method has proved to be promising also in the field of energy policy, being an effective solution for analysing current energy systems conditions (highlighting its positive and negative factors) and for assessing diverse strategic options, using interested experts' judgements for ranking them according to their capabilities of increasing strengths and opportunities and decreasing weaknesses and threats at once.

Chapter 5

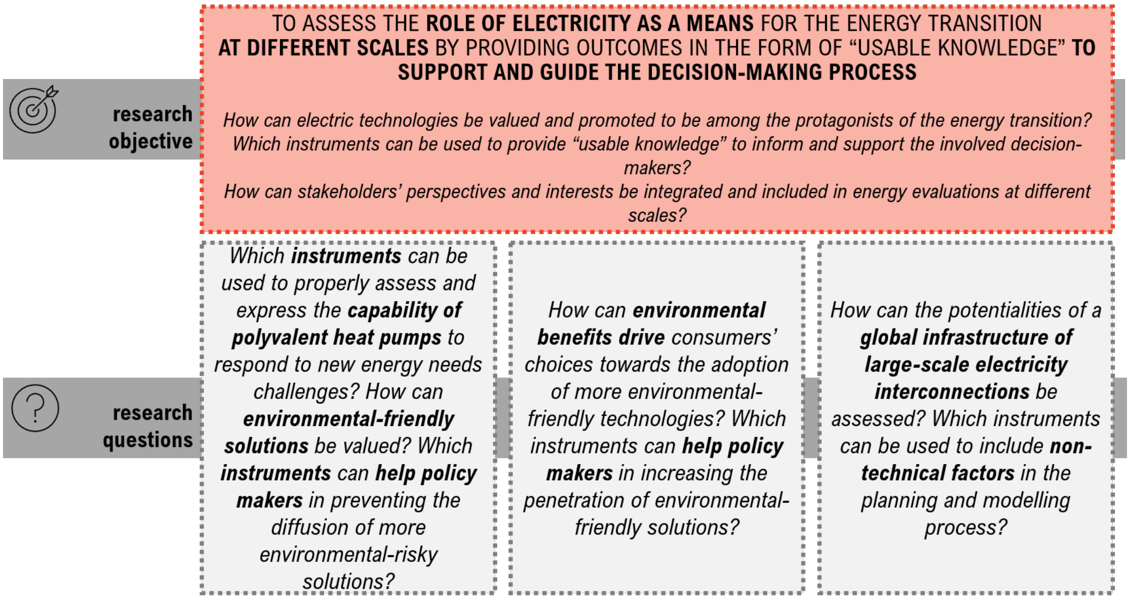
Concluding remarks

The critical consequences of climate change are urgently asking for a global action and an energy transition has already started, term used to indicate the needed changeover of sill not sustainable energy systems. Energy transition is usually correlated to a wider deployment of renewable energy sources, which in turn is reflected in a higher electrification of final uses, with a particular attention on heating and transportation sectors. As discussed, renewables, energy efficiency, electrification are usually perceived as the pillars of the modern energy transition, bringing multiple benefits (also non-energy-related), leading to the desirable decarbonization of energy systems and, thus, responding to the current challenges the world is facing (i.e. energy security, energy equity, environmental sustainability). The PhD activities well fitted in this context, encouraged by the external *stimuli* coming from international and national collaborations. In particular, the PhD pathway was developed aiming to study and assess the role of electricity as a means for the energy transition, declining it at different scales and with diverse focuses, in line with the "electricity triangle" concept. In particular, the core chapters of the PhD dissertation explored specific transition challenges (introduced in Chapter 1), focusing both on demand-side and supply-side considerations and targeting the main stakeholders potentially affected by these transformations.

The research pathway has highlighted how energy transition cannot be assessed in purely technical terms, since energy systems are encapsulated in social, economic, environmental and political/geopolitical spheres, which cannot be neglected when developing energy planning studies, regarding different sectors, services and at diverse time and spatial scales. In line with this, attention has been devoted to the role that science plays in assisting decision-making processes at different levels, with the scope of providing outcomes in the form of "usable knowledge", accessible also by a non-expert audience. Specifically, the research pathway is characterized by three overarching questions, aimed to identify the key instruments to be used to value and promote electric technologies, to synthesize and include stakeholders' perspectives into energy studies and to support the decision-making process.

These considerations have led to the definition of a general multi-layered methodological approach, to respond to the current challenges set to science, which should effectively provide evidence-based outcomes, easily understandable by policy makers, to support and guide the decision-making processes. The methodological approach, combining multi-dimensional tools with energy modelling and scenario analysis, was applied at different scales, from technological (Chapter 2), to national (Chapter 3), to European and global (Chapter 3), focusing on specific energy transition issues, ranging from the increasing electrification of end-uses (concentrating on the building sector), to the need for stronger policy support for transmission expansion planning.

The differences between the analysed applications were tackled, in terms of level of knowledge, research objectives and targeted audience, tailoring the methodological approach to the specific analysed contexts. The main conclusive remarks are summarized below.



Micro scale context

Starting from the micro scale, two applications were presented, both highlighting the role that energy efficient and sustainable HVAC systems play in the transition of the building sector. Attention was mainly devoted to electric solutions, thanks to their high energy efficiency and low environmental impact, if coupled with renewable energy sources. Both applications aimed to value electric technologies, thanks to the development of ad-hoc analytical tools (i.e. simple or aggregate KPIs), even if with different objectives and targets.

Specifically, the first application was market-oriented, devoted to the valorization of the polyvalent heat pump technology, a promising electricity-fuelled solution able to simultaneously meet cooling and heating demands with a single machine. To this purpose, the study focused on the characterization of the units operation dynamics and on the definition of ideal representative loads, dependent on three variables (i.e. contemporaneity, load intensity, and location), but not related to specific building typologies or real profiles. The work aimed to define new component- or system-level KPIs, to fill the existing normative gap and, thus, to respond to the need of commercial stakeholders to measure and appropriately enhance the potentialities of the polyvalent heat pump technology from a technical perspective with suitable metrics. Moreover, appropriate KPIs were identified to compare the performances of services provision of the polyvalent technology with more traditional electric HVAC configurations on a multi-dimensional basis. In particular, the comparison allowed to drawn some interesting considerations on the potentialities of the polyvalent heat pumps, which can represent a good balance between technical, financial and environmental aspects, highlighting the need to get a multi-perspective point of view when assessing and comparing the performances of alternative technological solutions.

The latter consideration opened the way to the second application, which developed a multi-perspective and multi-dimensional aggregate indicator (i.e. "Global Cost per Emissions Savings", GCES) to assess and compare the competitiveness of the electric heat pump with other widespread non-electric solutions (i.e. condensing gas boiler and biomass boiler) for residential buildings. The analysis was concentrated on the characterization of the operational conditions in which the technologies would operate, taking advantage of the reference building approach, aiming to assess the dependence of the technologies performances on the archetypes characteristics. In particular, the aggregate indicator was developed to combine the financial and environmental performances of the compared technological solutions for residential buildings into a single metric to quantify the trade-off between them. In doing so, the developed GCES index allowed to integrate the different and often contrasting perspectives of the stakeholders involved in the renovation process (i.e. private investors' and policy makers' perceptions and priorities in case of building retrofit), in order to synthesize the interests associated to the buildings renovation and to identify the potential risks for the policy makers associated to financially-driven individual choices. Indeed, the study started from the consideration that usually environmental-friendly solutions are still less financially attractive for the consumers; nevertheless, to push the transition of the sector, policy makers should act in order to prioritize environmental-friendly solutions, developing proper measures able to render them more profitable and attractive from a private standpoint. With this in mind, the aggregate GCES indicator was developed based on the conflict between the private benefit in selecting the most financially attractive solution and the public risk associated to the environmental impact that the private choice would induce, in case the most financially convenient solution is at the same time the most environmentally risky. The work aimed to offer to policy makers specific graphical and analytical instruments, to properly value more environmental-friendly technologies, while disadvantaging the diffusion of more environmental-risky solutions. Thanks to the development of different policy scenarios, it was possible to explore the effects that ad-hoc policy strategies may have on the future reciprocal competitiveness of the analysed technologies on the medium- and long-term. The work allowed to disclose information on widespread technologies for space heating purposes, assessing the environmental benefits (or risks) that their adoption in specific reference buildings would guarantee (or generate). The analysis was developed to forecast and assess the reciprocal competitiveness of the technologies under investigation on the medium- (2030) and long-term (2050), to support the future energy planning of renovation strategies for the building sector. In line with the policy-based goal of reducing the environmental impact of the building sector, the application discussed on the instruments at disposal of local/regional/national policy makers to translate the environmental burdens of some solutions into financial terms, in order to push the diffusion of more environmental-friendly options. The work highlighted how the development of aggregate indicators for the assessment of renovation strategies can be useful for the development of scenario analyses to forecast their penetration in the stock, giving an indication of the possible retrofit choices of the consumers.

Meso scale context

To address the latter consideration raised by the micro scale application, a shift of scale was needed, moving the lens from a technological assessment to a national perspective, studying possible pathways towards the decarbonization and electrification of the Italian residential sector. Moving from individual building models (i.e. reference buildings) to a whole national building stock model, the analysis reported a technological-oriented study, aiming to identify the medium- and long-term electrification potential of the Italian residential building stock, as well as to estimate the contribution of the forecasted electrification pathway to the overall reduction of energy consumptions and emissions.

The reference building approach was deployed in order to characterize and represent the Italian residential building stock. In line with the micro scale context, attention was devoted to the definition of relevant KPIs able to synthesize the private and public perspectives and to drive and reflect consumers' choices in case of retrofit of existing buildings. However, differently from the previous application, which used the developed GCES indicator for policy-oriented purposes, a newly-defined aggregate indicator (i.e. "Global Cost per CO_2 emissions Avoided", GCCA) was defined and deployed as a forecasting instrument, to assume consumers' choices in case of retrofit of the generation system, analysing an hypothetical condition in which consumers' retrofit decisions are not driven only by financial attractiveness and convenience, but are also influenced by the environmental benefits that the alternative generation technologies can guarantee with respect to the original conditions of their households systems. Scaling up the analysis from the individual RB to the entire building stock, the analysis of future possible technological uptake trends in the thermal uses in the Italian residential sector was performed through the comparative assessment of competing technological options to be potentially installed when a system retrofit occurs. Specifically, priorities of intervention in the stock were identified aiming to reduce the buildings environmental impact, while technological shifts were forecasted based on the minimization of the new GCCA indicator. Indeed, the GCCA was used to compare different technological solutions, valuing their capacity of reducing the environmental impact (in terms of CO_2 emissions) of the existing buildings.

Through this optimization approach, it was possible to forecast an hypothetical (even though probable) scenario, in which future policy actions would be based on the carbon intensity of the technological solutions at disposal and, thus, would push private decisions towards the adoption of more low-carbon technologies. Based on the scenario analysis, it was possible to discuss on the electrification potential of the residential sector, associated to the penetration of heat pumps for thermal uses, and on the positive consequences of this pathway in terms of energy and environmental impacts (both global and local) reduction.

Macro scale context

Moving from demand-side (i.e. building sector electrification issue) to supply-side analyses, attention was devoted to power system considerations. Specifically, the application at macro scale focused on the assessment of a power system configuration, in line with the Global Energy Interconnection (GEI) vision, assuming the presence of a global grid permitting to transfer clean energy from RES-rich areas (i.e. Equatorial and Arctic regions) to the major load centres and exploring the associated challenge of transmission expansion planning at global and European scales.

The first analysis allowed to simulate a simplified global grid for estimating the potential capacities of the interconnections for the highest demanding conditions (winter peak load day), under the premises of different policy scenarios, developed starting from literature research, including the GEI vision. Optimal power flow analysis was performed considering a large-scale interconnection structure and the presence of a global electricity market, allowing to evaluate a cost-optimal RES deployment, as well as to estimate the power flows from regions with favourable RES potentials to those with less favourable conditions. The work defined a set of global- and regional-based KPIs to study the potentialities and implications of a large-scale electricity interconnections implementation and to compare the scenarios from a multi-dimensional perspective. The analysis highlighted the complexity behind the implementation and planning of such global infrastructure, since the power expansion planning topic is intrinsically multi-dimensional, characterized by different factors, perspectives and interests. In particular, besides the importance of developing large-scale models for the assessment of this energy paradigm, the work at global scale stressed the importance of integrating also non-technical aspects into energy planning considerations and of supporting the definition of energy policies through the use of appropriate multi-dimensional techniques and approaches, able to tackle the various facets of energy issues and to consider the possible perspectives, interests and concerns of the involved stakeholders.

The latter consideration was deepened in the second application, aiming to explore the capability of evaluation tools to synthesize the complexity of the large-scale transmission expansion planning topic and, thus, to guide the decision-making process for its implementation. Specifically, the application made use of multi-criteria methods, which are considered as interesting tools to guide policy makers to articulate or explore plans representing the best trade-offs between multiple (and often contrasting) objectives. Moving from a global- to a European-based perspective, the analysis aimed to highlight how a GEI-based framework would pose challenges on regional grids, affecting the distribution of the internal power flows. The hybrid A'WOT method (resulting from the combination of SWOT and AHP multi-criteria analyses) was introduced to guide interested stakeholders to define the most appropriate strategies for European intercontinental interconnections, highlighting the opportunities and obstacles associated to the alternative strategies at disposal. After an initial phase of problem statement and assessment, different high-level, multi-dimensional and national-based criteria were selected, according to which the proposed strategic alternatives were assessed, correlating different strategic factors belonging to diverse domains, also thanks to the judgements expressed by the involved experts. The A'WOT method was applied to identify the set of European countries most suitable for hosting interconnection projects with the main neighbouring areas (i.e. Africa, Arctic region, Eurasia, Russia, China), in line with the GEI vision. In other words, based on the A'WOT outcomes, the assessed European countries were classified and compared, aiming to identify the best strategies of interconnections. Besides the interesting exploitation of multi-criteria methods to transmission expansion planning at a high-level territorial scale, the application represented the basis for a further investigation on the possibility of combining multi-criteria outcomes with traditional power system modelling techniques. Indeed, the results of the hybrid A'WOT method were used to identify the interconnectors needed in each European country under the premises of a GEI scenario; these results were then used as input to a multi-objective optimization approach, which allowed to identify the optimal allocation of the accessing nodes in each country, aiming to minimize the network overload and the cost of generating electricity. The analysis, run for the peak load hour, was developed to study the capacity of the European grid to accommodate new power flows distributions, associated to the hypothetical GEI realization, as well as to identify the countries most likely to be affected by this extreme power system paradigm. Proper regional- and national-level multi-dimensional metrics were used to assess the potential consequences of a GEI vision on Europe.

5.1 Looking forward

"The energy transition is possible and it is affordable.
It is of utmost importance that we look at the transition
not as a burden, but as on opportunity"
Rainer Baake [1]

The PhD dissertation aimed to emphasize the role of electricity as a means for the energy transition, showing its potential benefits associated to higher efficiency at end-use level (e.g. thanks to the exploitation of heat pumps for heating and cooling purposes), lower environmental impact (if electricity is generated by increasingly cleaner generation mix), lower social externalities (e.g. lower health-related costs associated to environmental burdens) and higher security of supply. Supported by the presented applicative studies, the PhD pathway has highlighted the complexity of the energy transition phenomena, which realization will depend on multiple factors, technologies and actors. Energy transition is affecting each aspect of the energy chain, embracing people needs and expectations and asking for sustainable and efficient technologies to take hold in the market. An effective policy framework is fundamental to guarantee a sustainable, efficient and effective transformation process and the role of science in supporting and guiding the decision-making has been deeply discussed. Moreover, since the impacts and benefits of energy transition processes cross the boundaries of energy systems, affecting also environmental and socio-economic domains, it is fundamental to identify multi-disciplinary methodological approaches, as the one proposed, in order to integrate the different dimensions into the modelling and forecasting of energy systems.

The PhD work does not presume to be exhaustive or to provide a "one-size-fits-all" theory, but has allowed to spotlight some challenging topics in the framework of the energy transition, pinpointing key technologies and actors that will be core protagonists of the transition and identifying or developing instruments aiming to support and guide the decision-making process, in different contexts of analysis and with diverse objectives. To this purpose, a multi-layered, multi-scale and multi-perspective general methodological approach was conceptualized and tailored on the specific applicative studies, developed also thanks to the external *stimuli* coming from international and national collaborations.

[1] State Secretary in the Economy Ministry of Germany, 2017.

In particular, the research work permitted to point out the main research keywords: **dimension/layer**, to study and assess energy transition challenges considering the interactions of the dimensions that are touched by or can influence the phenomenon under investigation; **scale**, to tailor the methodological approach depending on the context of analysis; **stakeholders' involvement**, to target the main actors involved in or influenced by the phenomenon under study and to consider their main perspectives, expectations or decisions, being them the core protagonists of the transition process; **KPIs**, to measure energy systems performance, to set and monitor medium- or long-term objectives, to support the decision-making process or to inform stakeholders; **scenario analysis**, to estimate the evolution of the phenomenon under study in time (medium- or long-term analysis) and in accordance with policy measures or market evolutions; **synthesis**, to highlight the need for multi-dimensional tools able to integrate different perspectives and dimensions to describe or to drive the phenomenon under study.

The research opens the way to further development, to improve and validate the obtained findings. For each application, the main limitations and future analyses were described at the end of each core chapter. Some final considerations can be drawn. Regarding the building sector, more efforts are needed in order to study the impact of a higher penetration of electric technologies on the power grid, accenting possible critical issues or rooms for improvement. Due to the evolution of energy demand characteristics, the impacts of the increment of air conditioning needs on buildings operations and on power sector must be carefully studied.

Furthermore, in accordance with the GEI vision, the analysis represented a preliminary attempt to model and simulate the operations of a large-scale and centralized RES-based energy paradigm and to explore possible methods to integrate common non-technical parameters (e.g. social acceptance, regulatory quality, technical maturity, etc.) into traditional power system modelling. The modelling framework should be improved and other evaluation tools could be studied, as cited. In this context, moreover, system dynamics or agent-based models could be evaluated as potential new perspectives for these analyses, being able to model and simulate energy systems considering and integrating different agents' decisions.

Nomenclature

2DS: 2° Degree Scenario
AC: Alternate Current
ACI: Aggregate Contemporaneity Index
AHP: Analytic Hierarchy Process
ANP: Analytic Network Process
AWI: Annual Weighted Index
BAU: Business As Usual
BRI: Belt and Road Initiative
C: Component
CO_2: Carbon Dioxide
COP: Coefficient of Performance
COP21: Conference of Parties 21
CPC: Cooling only Performance in Contemporaneity hours
CPnC: Cooling only Performance in non Contemporaneity hours
CSC: Current-Source Converter
DC: Direct Current
$\Delta C_I\%$: Δ Investment Cost
$\Delta C_e\%$: Δ Energy Cost
DSO: Distribution System Operator
DHW: Domestic Hot Water
EER: Energy Efficiency Ratio
ENTSO-E: European Network of Transmission System Operators
ETP: Energy Technology Perspectives
EU: European Union
EPBD: Energy Performance of Buildings Directive
GCCA: Global Cost per CO_2 emissions Avoided
GCES: Global Cost per Emissions Savings
GDP: Gross Domestic Product
GEI: Global Energy Interconnection
GEIDCO: GEI Development and Cooperation Organization
GHG: Greenhouse Gas
HDD: Heating Degree Days

HP: Heat Pump
HPC: Heating only Performance in Contemporaneity hours
HPnC: Heating only Performance in non Contemporaneity hours
HVAC: Heating, Ventilation and Air Conditioning
HVAC*: High Voltage Alternative Current
HVDC: High Voltage Direct Current
IE: Increased Efficiency
IEA: International Energy Agency
JRC: Joint Research Center
KPI: Key Performance Indicator
LCA: Life-Cycle Assessment
LCOE: Levelized Cost of Electricity
LTRS: Long-Term Renovation Strategy
MCDA: Multi-criteria Decision Analysis
MFH: Multi-family House
MS: Member State
NET: Net Electricity Trading
NSLP: Non-Satisfiable Load Percentage
O&M: Operation & Maintenance
OPF: Optimal Power Flow
PHP: Polyvalent Heat Pump
PL: Partial Load
PM: Particulate Matter
PV: Photovoltaic
PVGIS: Photovoltaic Geographical Information System
RB: Reference Building
REP: Real Policy
RES: Renewable Energy Sources
S: System
SCOP: Seasonal Coefficient of Performance
SEER: Seasonal Energy Efficiency Ratio
SFH: Single-family House
SH: Space Heating
SHCPC: Simultaneous Heating and Cooling Performance in Contemporaneity hours
SRI: Smart Readiness Indicator
SWOT: Strengths, Weaknesses, Opportunities, Threats
TABULA: Typology Approach for Building Stock Energy Assessment
TFC: Total Final Consumption
TPC: Total Performance Coefficient
TSO: Transmission System Operator
TPES: Total Primary Energy Supply
TYNDP: Ten Year Network Development Plan

UN: United Nations
UHV: Ultra High Voltage
WEC: World Energy Council
WEO: World Energy Outlook

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Appendix

Appendix A

The criteria used in the hybrid A'WOT application are here reported.

Technical criteria

- electric power transmission losses: losses in electric power transmission system, expressed as percentage of the output [230].
- congestion in national power grid: congestion of the national grid, considering the total internal load of the country and the total internal capacity of the power system [224].
- existence of interconnection structure: cross-border capacities between a country and the surroundings [224].
- number of smart grid projects: number of concluded and on-going smart grid projects [231].
- concentration of national whole-sale market: measured by Herfindahl-Hirschman Index (HHI), which is "a common measure of market concentration used to determine market competitiveness. The closer a market is to a monopoly, the higher the market's concentration" [232].

Economic criteria

- investment in electricity transmission: investment cost breakdown for reaching 15% interconnection target by 2030 [224].
- inflation: measured by consumer price index, it is defined as "the change in the prices of a basket of goods and services that are typically purchased by specific groups of households" [230].
- cost of money (price level index): "the price level index expresses the price level of a given country relative to another (or relative to a group of countries like the European Union), by dividing the purchasing power parities by the current nominal exchange rate" [36].

- cost of business start-up procedures: percentage of the gross national income, which is the sum of value added by all resident producers plus any product taxes (less subsidies) not included in the valuation of output plus net receipts of primary income (compensation of employees and property income) from abroad [230].

- time required to start a business: number of days required to start a business [230].

- income inequality (GINI coefficient): GINI coefficient is a measure of statistical dispersion intended to represent the income or wealth distribution of the residents of a nation [230]. It is a common metric for economic inequality.

- employment rate: rate of people aged 20 to 64 in employment with respect to total population of the same age group [36].

- electricity prices: electricity prices for medium size households, expressed in €/kWh [36].

Socio-political criteria

- political stability: "likelihood perceptions of political instability and/or politically-motivated violence, including terrorism" [233].

- government effectiveness: "perceptions of the quality of public services, of the civil service and the degree of its independence from political pressures, of policy formulation and implementation, and the credibility of the government's commitment to such policies" [233].

- regulatory quality: "perceptions of the ability of the government to formulate and implement sound policies and regulations that permit and promote private sector development" [233].

- control of corruption: "perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as "capture" of the state by elites and private interests" [233].

- presence of subsidies: subsidies expressed as percentage of total expense [230].

- social acceptance of RES installation: percentage of people considering important that the national government sets targets to increase the amount of renewable energy [234].

- socio-economic energy risk index: overall risk of a country that consists of political-institutional, socio-political, economy-driven and intrinsic energy risks, from Risk of Energy Availability: Common Corridors for Europe Supply Security (REACCESS) project [235].

Energy-environmental criteria

- CO_2 emissions: CO_2 emissions in the different countries [36].
- electrical load growth: load projections up to 2050 [32].
- current electrification of final uses: share of electricity in final energy consumption [36].

Appendix B

This Appendix collects the papers published during the PhD. Parts of these publications were previously cited within the dissertation, as a support to the developed research activities.

- C. Becchio, S.P. Corgnati, M. Vio, **G. Crespi**, L. Prendin, M. Magagnini, *HVAC solutions for energy retrofitted hotel in Mediterranean area*, Energy Procedia 133, pp. 145-157, 2017.

- M. Vio, C. Becchio, S.P. Corgnati, **G. Crespi**, M. Babuin, S. Morassutti, *The Polyvalent heat pumps technology in retrofit of existing HVAC systems*, Energy Procedia 133, pp. 158-170, 2017.

- C. Becchio, S.P. Corgnati, M. Vio, **G. Crespi**, L. Prendin, M. Ranieri, D. Vidotto, *Toward NZEB by optimizing HVAC system configuration in different climates*, Energy Procedia 140, pp. 115-126, 2017.

- E. Bompard, **G. Crespi**, D. Grosso, F. Profumo, P. Boccardo, *Energy-geomatics characterization of open-sea energy corridors in the framework of energy security. A case study: LNG from Qatar*, book chapter in: "Italian Maritime Economy – China, energy corridors, ports and new routes: geomaps of a changing Mediterranean. SRM 5th Annual Report", 2018.

- **G. Crespi**, C. Becchio, M. Bottero, T. Huang, E. Bompard, S.P. Corgnati, *Multi-criteria approach to transmission expansion planning in Europe*, proceeding of "4th Energy for Sustainability International Conference 2019 - Designing a Sustainable Future", Turin, 2019.

- **G. Crespi**, Z. Han, T. Huang, E. Bompard, S.P. Corgnati, *A simplified electrical network model for techno-economic analysis of globally integrated electricity market*, proceeding of "4th Energy for Sustainability International Conference 2019 - Designing a Sustainable Future", Turin, 2019.

- V.M. Barthelmes, **G. Crespi**, M.V. Di Nicoli, C. Becchio, V. Fabi, S.P. Corgnati, *Profiling Occupant Behaviour in Italian Households for enhanced building simulation input: Insights into a Survey-based Investigation*, proceeding of "16th Conference of International Building Performance Simulation Association (IBPSA)", Rome, 2019.

- **G. Crespi**, C. Becchio, S.P. Corgnati, *Retrofit scenarios for emissions reduction in Italian hotels towards a Post-Carbon City*, proceeding of "16th Conference of International Building Performance Simulation Association (IBPSA)", Rome, 2019.

- E. Bompard, **G. Crespi**, *La dimensione energetica delle Nuove Vie della Seta*, ORIZZONTE CINA, vol. 10, n. 3., pp. 15-20, 2020.

- **G. Crespi**, E. Bompard, *Drivers of energy transition of Italian residential sector*, REHVA Journal, vol. 57, Issue 1., pp. 6-10, 2020.

- I. Abbà, **G. Crespi**, S.P. Corgnati, S. Morassutti, L. Prendin, *Sperimentazione numerica delle dinamiche di funzionamento di sistemi polivalenti*, proceeding of "37° Convegno Nazionale AiCARR", 2020.

- I. Abbà, **G. Crespi**, C. Lingua, C. Becchio, S.P. Corgnati, *Theoretical and actual energy behavior of a cost-optimal based Nearly-Zero Energy Building*, AICARR Journal, vol. 62, n. 3., pp. 36-39, 2020.

- Z. Han, **G. Crespi**, T. Huang, X. Tan, Z. Ma, F. Yang, H. Huang, *Development of European Power Grid and Its Compatibility with Global Energy Interconnection*, DIANLI JIANSHE vol. 41, n. 11, pp. 1-11, 2020.

- E. Bompard et al., *Electrify Italy*, Fondazione Centro Studi Enel, 2020.

- **G. Crespi**, C. Becchio, S.P. Corgnati, *Towards Post-Carbon Cities: Which retrofit scenarios for hotels in Italy?*, Renewable Energy 163, pp. 950-963, 2021.

- **G. Crespi**, C. Becchio, T. Buso, S.P. Corgnati, *Environmental performances in green labels for hotels - a critical review*, book chapter in: "Bevilacqua C., Calabrò F., Della Spina L. (eds) New Metropolitan Perspectives. NMP 2020. Smart Innovation, Systems and Technologies. Springer", vol. 178, pp. 1176-1186, 2021.

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- C. Becchio, **G. Crespi**, T. Binda, S.P. Corgnati, *Air pollution and health effects: review of indicators and evaluation methods*, proceeding of "15th ROOMVENT Conference - Energy efficient ventilation for healthy future buildings", 2021.

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