

Bridging Research and Policy in the Context of National and European targets: decarbonization of the Italian energy system

Caterina Carà
Energy Center Lab
MOREnergy Lab
Politecnico di Torino
Turin, Italy
caterina.cara@polito.it

Enrico Giglio
MOREnergy Lab
Politecnico di Torino
Turin, Italy
enrico.giglio@polito.it

Paolo Marocco
Dipartimento Energia
"Galileo Ferraris"
Politecnico di Torino
Turin, Italy
paolo.marocco@polito.it

Mauro Bonfanti
MOREnergy Lab
Politecnico di Torino
Turin, Italy
mauro.bonfanti@polito.it

Giuliana Mattiazzo
Energy Center Lab
MOREnergy Lab
Politecnico di Torino
Turin, Italy
giuliana.mattiazzo@polito.it

Abstract—This paper critically reviews Italy’s energy decarbonization efforts, analysing both EU and Italian policies and the relevant academic literature. It examines the policy- and research-driven aspects of the transition, focusing on their mutual alignment. The analysis highlights four main findings: 1) the EU and Italian medium and long-term targets are periodically updated and kept the same, only becoming more stringent without facing specific vertical criticalities; 2) the technical implementation limitations are overlooked, showing the tendency of EU and Italian policies to focus only on providing insights rather than tangibly supporting the implementation phase; 3) the results of the scientific literature show a strong coherence, presenting the possible elements for decarbonization, without providing real impactful results; 4) the literature studies support medium and long-term strategies with technical insights.

Index Terms—decarbonization, energy system, planning, power-to-X, renewable energy sources, policies

I. INTRODUCTION

Climate change is a well-recognized and ongoing global issue strongly linked to anthropogenic activities and directly impacting both the environment and human society. In 2023, the European Union (EU) final energy consumption was predominantly reliant on oil, petroleum products, natural gas, and electricity, with renewable energy and biofuels representing the smallest share [1]. Therefore EU is placed among the world’s largest emitters, accounting for approximately 6% of global greenhouse gases (GHGs) emissions [2]. This fossil fuels dependency severely undermines the energy security [3], especially in times of political tension [4]. Italy is one of the largest contributors to EU emissions, also proven by its 2023 electricity demand supply largely met by fossil fuel-based thermoelectric plants (45.6%), while variable renewable energy sources (VRES), mainly including photovoltaic (PV)

and onshore wind (OW), accounted for only 17.5% [5]. To address and contain climate change evolution and supporting the transition to a more sustainable energy system, the EU and its Member State have implemented a wide range of energy and climate policies aimed at reducing GHGs emissions, supporting a sustainable energy systems development and safeguarding natural resources [6].

In this context, this paper examines the Italian energy transition process from two key perspectives: government policy and scientific research. The aim is to critically analyse the path taken in the transition, highlighting the dynamics of Italian national policies and their links with EU policies and the scientific community. Similar analysis can be found in literature referring to other EU countries [7]–[11].

The Italian case decarbonization case study is assessed by proceeding with the following research questions:

- *Are the main driver targets in the middle and long term leading to any changes in energy transition path?*
- *Is there consistency between policy targets and the practical limitations of technical implementation?*
- *Considering the Italian clean energy transition context, is there any coherence in the literature outcomes?*
- *Are the research studies supporting the medium-term Italian policies strategy implementation?*

To answer these questions, the study adopts a top-down review approach over a selected 15-year period. It begins with an analysis of EU plans and directives, proceeds through Italian government strategies and concludes with a critical evaluation of academic literature.

II. EUROPEAN AND ITALIAN PLANS AND DIRECTIVES

In this section, a chronological overview of European and Italian strategies and directives is proposed, highlighting the cardinal steps and targets for climate change containment.

In the context of the EU, climate agendas have set ambitious targets to align with key strategies defined starting from the 1997 Kyoto Protocol [12] and continuing with the 2015 Paris Agreement [13]. Over the past 15 years, the EU Commission and Parliament have issued specific guidelines for Member States to follow in the fight against climate change and in the transition to a low-carbon economy. Specifically, there are two categories of policies related respectively to strategic adaptation measures due to climate change and to ambitious programs to change socio-economic behavior with respect to our not sustainable society.

In 2009 EU Parliament and the Council emanates the Climate and Energy Package "20-20-20" [14], setting a series of targets aiming at ensuring the realization of ambitious climate and energy objectives for 2020, by means of three key target: 20% GHGs emission reduction, 20% of energy consumption covered by renewable energy sources through the first Renewable Energy Directive 2009/28/EC (RED I) [15], and 20% energy efficiency improvement. The 2013 EU Strategy on adaptation to climate change [16] sets out frameworks and mechanisms for taking the EU preparedness for current and future climate impacts, highlighting that though the effort for limiting the global warming below 2°C compared to pre-industrial level, climate change impacts over decades will still occur due to the delayed effects of the past and current GHGs emissions. In 2015, the EU Commission delivers the "Energy Union Strategy" [17], integrating energy and climate policies to achieve post-2020 targets, creating an Energy Union based on defined pillars, namely sustainability, security and competitiveness in the energy dimension. In parallel, Italy, as an EU Member State, is proposing a set of national strategies and targets tailored to its national context and in line with EU objectives. In 2015, the "*Strategia Nazionale di Adattamento ai Cambiamenti Climatici*" (SNAC) [18] is delivered by the Ministry of the Environment and Safeguard of Land and Sea, analyzed climate change impacts considering the main environmental and socio-economic sectors, also proposing a series of action areas. In 2017, the "*Strategia Energetica Nazionale*" (SEN) [19], promoted by the Ministry of the Economic Development and the Ministry of the Environment and Safeguard of Land and Sea, is outlined considering the critical Italian context both at economic and environmental level. Specifically, the energetic sector is identified as a key area for driving the country's growth. Besides, this plan is developed within the framework of sustainable development, without any binding EU mandates, positioning Italy as one of the pioneering Member States in this area. Moving to the EU perspective, further efforts are destined to RES strategic deployment. Indeed, with the Renewable Energy Directive 2018/2001 (RED II) [20] in 2018, a target of RES share in the final gross energy consumption is set equal to 32% by

2030 and in the transport sector at least equal to 14% of its final energy consumption. The EU Directive 2018/2002 [21] of the EU Parliament and the Council propose a new target for energy efficiency, aiming for a 32.5% reduction in projected energy consumption by 2030.

Subsequently, in 2018 the EU Regulation 2018/1999 on the Governance of the Energy Union and Climate Action [22] aims at shaping strategies for the implementation of emissions policies, in line with [13] and the objectives of the [17]. It includes specific key measures, namely the development by Member States of national energy and climate plans for the 2021-2030 period, with periodic updates, as well as the creation of 30-year strategies for emissions reduction aligned with [13]. Keeping up with the EU target evolution, the proposal of the "*Piano Nazionale Integrato per l'Energia e il Clima*" (PNIEC) in 2018 [23] has been elaborated by the Ministry of the Economic Development, the Ministry of the Environment and Safeguard of Land and Sea, and the Ministry of Infrastructure and Transport. The Italian plan is subsequently integrated along 2019 taking into account the novelties of the *Decreto Clima* [24] in matter of air quality (in 2019 Italy was the first EU country with premature deaths due to particulate matter exposure) and of the European Green New Deal [25], and finally submitted to the consultation with the EU Commission and published in 2019 [26]. Besides, in 2019 the EU Green Deal [25] set out various initiatives aimed at achieving net carbon neutrality by 2050, and in 2021 the EU Commission writes into binding law the Green Deal target for Europe economy and society to become carbon-neutral by 2050. Thus, from the comprehensive union of the different identified issues and targets, Italy publishes in 2019 the finalized first version of a national strategy [26], identifying specific objectives and targets in differentiated areas: decarbonization through tailored measures related to GHG emissions and RES, energy efficiency, energy security, improvement of the internal energy market through measures related to electricity interconnection and transmission infrastructure, energy poverty, research innovation and competitiveness. In 2021, stemmed from the EU Green Deal, the Fit for 55 Package [?] set out defined measures and proposals to achieve the 55% GHGs emissions reduction by 2030 compared to 1990 levels, including reforms in various sectors, such as energy, transport, agriculture, industry. The European Climate Law in 2021 [27] writes into law the goal set in the EU Green Deal [25] for EU economy and society to become climate neutral by 2050, with the intermediate goal of GHGs emissions reduction by at least 55% 2030 compared to 1990 levels. In 2021, the European Commission adopts a new Strategy on the Adaptation to Climate Change [28] in response to the unavoidable impacts of climate change and thus highlighting the importance of becoming climate resilient by 2050. In 2022, the REPowerEU [29] proposes guidelines to end the EU energy dependency by diversifying provisions and accelerating the transition to clean energy, increasing the deployment of RES into the energy mix and taking measures to address infrastructure and regulatory bottlenecks. In 2023, the revised Renewable Energy Directive 2023/2413/EC (RED

III) [30] sets an overall RES target of at least 42.5% in energy consumption, binding at EU level by 2030 aiming at 45%, and outlined a list of recommendations for EU countries to transpose the elements of the directive into national law. In the same year, also the EU Directive 2023/1791 [31] of the European Parliament and of the Council is delivered, setting a binding target to improve energy efficiency to reduce EU's energy consumption by at least 11.7% by 2030 compared to the EU projection, updated with respect to Fit for 55 Package [?]. In 2023, Italy proposes the "*Piano Nazionale di Adattamento ai Cambiamenti Climatici*" (PNACC) [32], which aims to provide a national framework for the implementation of actions to limit the consequences and risks of climate change, while trying to take advantage of the new opportunities that the new climatic conditions may offer. Finally in 2024, Italy presents the new updated version of the "*Piano Nazionale Integrato per l'Energia e il Clima*" (PNIEC) [33] which proposes a new strategy defining internal targets for the achievement of specific objectives, keeping the same framework and updating the targets compared to the 2019 PNIEC, in line with the 2030 target year. The 2024 PNIEC recognizes the significant gap in the achievement of the 2019 PNIEC targets, caused by overly ambitious objectives, barriers to renewable energy project approvals and the impact of the recent crises. The 2024 PNIEC highlights the need for pragmatic, achievable solutions to meet Europe's new 2030 emission reduction targets, while addressing the challenges and constraints identified in previous years. Table A.2 summarizes the above mentioned main European and Italian climate change targets and related policies and strategies. It is worth noting that since climate change was identified as a problem and the EU decided to address it and mitigate its effects, several steps have been taken to guide Member States in a particular direction. Specific targets can be identified, often carried over from previous plans, confirming existing targets or improving on them, with the same target years of 2030 and 2050. Analyzing the EU's plans and strategies over the last two decades, three key points emerge: 1) EU targets mainly rely on GHGs emission reduction, RES penetration increase, energy consumption (EC) decrease, energy efficiency improvement (EE) and electricity interconnections (EI) enhancement objective; 2) Target years are always kept the same, namely 2030, 2040, 2050; 3) Over time, the targets may become stricter, but the window of opportunity for their implementation is narrowing. Looking at the actual evolution of the EU, there is still a significant gap to reach the pre-defined targets, e.g. as shown by trends of GHG emissions evolution or RES increasing share in final energy consumption. Also in the Italian context, the gap between the current situation and the final targets is still significant. This can be seen, for example, in the slow progress of RES deployment. Even key actors, such as ministries, have acknowledged the inadequacy of the planned policy lines (see A).

III. RESEARCH TRENDS

In the context of climate and energy policies, also the scientific literature contributes in giving supports and insights related to the decarbonization of the Italian energy system, constraining the analysis with respect to European and Italian targets. In the 30 analyzed literature works, it is possible to identify three main analysis procedure implemented, either to provide a topical or a methodological contribution to the research world [34]–[36]. Besides, considering the methodological aspect, Figure A.3a illustrates the three main categories, showing how the main tendency is to adopt energy system optimization. Less used approaches are energy system simulation, where specific technology-based analysis is provided, and policy and strategy assessment using tailored criteria. Table A.3 summarizes the main features characterizing the various frameworks implemented in the studies. The primary tendency is to optimize the overall energy system by minimizing system costs, often through a single-objective function [37], especially when using ESOMs [38], [39]. Optimization is typically performed for single years corresponding to the target years set by European and Italian policies (2030 and 2050) [40], [41], allowing for high temporal (e.g., hourly) [42], [43] and spatial (e.g., electricity market regions) [44], [45] resolution. Actually, those choices are due to the main purpose of high VRES variability alongside energy demand (electricity, heating, cooling, etc.) representation, which directly affect optimal capacity sizing. Multi-regional spatial resolution is not always implemented, neglecting possible energy flows inter-regional connections. However, on the other hand there is a scarce share of studies providing long-term strategic perspectives that comprehensively outline decarbonization pathways [36], [46], [47]. Besides, in the reference energy system analyzed, as shown in Figure A.3b, there is a relevant tendency in including the power sector, namely including the electricity vector, and the transport sector, which also belongs to the hard-to-abate family. In addition, among the proposed scenario insights, there is an integration of policies in terms of boundary constraints, specifically the GHG emissions target for 2030 and 2050 [41], [48], and the RES penetration in gross final energy consumption by 2030 [36], [49], as set by various European strategies and also reflected in the Italian ones, which, however, lack strategies for 2050. It is important to emphasize that the results of the energy system configuration may vary depending on the different settings in each analysis, such as technical and cost assumptions, as well as the choice of spatio-temporal resolution. In order to better explore and deepen this aspect, a subset of studies are selected in Table A.3 to compare their main outcomes considering a fixed set of constraints of their analysis settings [50]–[53]. These selected studies investigate an energy system configuration at least composed by power, heating and transport sector, choose the same temporal hourly resolution which highlight impact the VRES sizing, have a multi-nodal approach for the spatial representation and set the same long term target of full decarbonization by 2050. Figure A.4 shows for PV

and OW technologies the divergency of the different studies optimal sizing with respect to the actual installed capacity in 2019, which is considered a common comparison measures, since there is no established capacity target for the Italian energy system by 2050. The percentage differences shown in the graph highlight the limited reliability of the capacity sizing results and show the volatility of the study's findings, where small changes in assumptions can significantly affect the results, when it comes to providing concrete, quantitative solutions for decarbonization by 2050.

As shown in Figure 1, elaborated considering all the papers listed in Table A.3, 10 key-words outcomes are identified in order to better emphasizes literature contribution in the definition of the Italian decarbonization process, where the larger the bubble the more that specific topic is stressed and found out from literature studies. Besides, it is also necessary to underline that there is an overlapping between those outcomes in-between various studies, and a mutual key findings interconnection, highlighting the importance of implementing a comprehensive approach.

RES ([36], [49], [54], [55]) are one of the key element of the decarbonization pathway, favored by the availability of free primary energy sources, by their competitive costs which thanks to the ongoing technological development are yearly decreasing and also projected to become even more convenient in the long term. Besides, RES deployment also allows for greater independence in terms of raw material imports, on which Italy has one of the highest dependencies in Europe. It also reduces the volatility of costs, which can vary drastically, and improves accessibility, which can be affected by supply unpredictable disruptions.

Hydrogen (H_2) ([38], [40], [56], [57]) is widely recognized as a fundamental energy vector due to its high flexibility, enabling sector coupling through various applications such as direct use as an e-fuel, blending into natural gas networks, conversion into other energy vectors and facilitating increased inter-regional and international energy exchanges. Another key advantage of H_2 is its capacity for seasonal storage, which is essential for managing VRES high penetration and addressing demand imbalances. This makes it critical for grid balancing, providing significant dispatchable power. However, challenges remain for its transport and storage. In addition, H_2 is contributing to the energy transition especially of hard-to-abate sectors such as transport and industry, although it is not yet cost-competitive.

Storage ([37], [42], [58]) facilities play a key role due to their flexibility, which helps to manage mismatches between VRES generation and demand. They contribute to reducing overall system costs, facilitating the integration of low-cost RES technologies, optimising system planning and operation, and improving security of supply.

Power-to-X ([39], [43], [59]) concept involves the conversion of one energy vector into another, such as e-fuels (hydrogen, synthetic natural gas) or electricity. Studies also highlight its critical role in balancing the system, especially under high VRES penetration, representing a flexible demand able to

absorb production surpluses from non dispatchable sources.

Electrification ([34], [41], [45], [46], [51], [53], [60], [61]) is a key transition strategy for energy sectors such as transport and heating, and also requires end-use electrification to position electricity as a primary energy carrier. While it faces technical and economic barriers in some areas, such as industrial processes, electrification enables CO_2 emissions reduction though depending on the primary energy source. It also increases the penetration of VRES in a cost-effective way, particularly in sectors that are better suited to the availability of renewables, such as transport.

CO_2 technologies ([39], [40], [43], [45], [47], [62]), including carbon capture, storage, and utilization, are considered essential for achieving carbon neutrality, especially for hard-to-abate sectors. Indeed, CO_2 technologies are crucial for compensating unavoidable emissions, though high abatement costs and efficiency limitations remain significant obstacles to their development.

Sector Coupling ([44], [50], [52]) concept is essential for cost-effective decarbonization through efficient cross-sector integration. Its benefits include optimal VRES sizing, direct e-fuels production enabled by interconnected energy vectors, and improved energy system adequacy and security through VRES counterbalancing.

E-fuels ([44], [50], [52]) such as hydrogen, ammonia, methanol and synthetic natural gas are essential for transitioning sectors such as industry and more in general those where electrification is not feasible (e.g. ammonia in agriculture). They enable emission reductions while reducing dependence on imported fuels and biomass. Although not yet economically competitive with fossil fuels, e-fuels can improve energy resilience by reducing exposure to fossil fuel price volatility.

Energy network ([35], [45], [63]) reinforcement of both existing electricity and natural gas network, also favoring the H_2 blending, and development of new infrastructure, destined for H_2 only, result fundamental for the configuration of a carbon-neutral energy system.

Over-countries ([35], [51], [53]) energy flows between neighboring countries, though largely excluded in most of studies also to emphasize Italy's energy independence, when included highlight the importance of cross-border connections in identifying cost-effective solutions and optimising the configuration of the energy system.

IV. DISCUSSION AND CONCLUSION

This paper provides an overview of the dynamic evolution of Italian energy transition policies over the last two decades, also incorporating scientific research contributions. It highlights the direct link between EU targets and Italian strategies to combat climate change, both in terms of mitigating its effects and preventing further damage. Over time, the EU has set ambitious medium- and long-term targets, such as the GHGs emissions reduction and the deployment of low-carbon technologies. In response, Italy's national plans have been aligned with these targets, setting specific sub-targets tailored to the country's context. Key elements for the energy

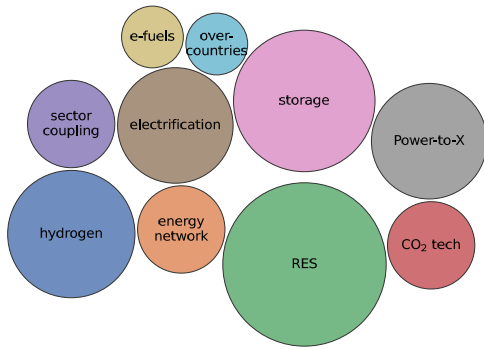


Fig. 1: Scientific literature key outcomes.

transition include the RES development, the reduction of energy consumption and the introduction of innovative CO₂ technologies, as outlined in Italy's strategic plans for 2017-2024 [19], [26], [33]. Also the scientific world has deepened the decarbonization process, assessing useful insights that can be often tracked down also in Italian policies. Thus the flow of climate change fight starts at European level, directly affecting the Member States policies development which are supported by the scientific world which insights and main outcomes can be found within national policies. Nevertheless, their main contribute is to provide insights which weakly affect the actual energy transition evolution.

Summarizing, from this review it is possible to answer to the four main questions proposed:

Are the main driver targets in the middle and long term leading to any change in energy transition path? European targets and Italian strategies tailored on the latter are updated going on in time becoming increasingly ambitious, without taking into account vertical policies focused on specific support and guidelines. An example can be the GHGs emission trend, which has been addressed since 2015 but the only evident variation was due to a specific crisis in 2020, subsequently facing a new increasing trend. Analogously, the RES penetration in the final consumption supply is weakly increasing from 2015 of less than 2% yearly increase, and expecting almost the double yearly increase in 6 years.

Is there any consistency between policies targets and technical implementation limitations? The Italian strategic plans, which are periodically updated, have critically acknowledged the ambitiousness of the past targets and have readjusted the strategy implementation steps, although the same long-term decarbonization result is expected, with a continuous reduction of the actual implementation time. Considering the literature side, notably, some works analyzing the Italian energy planning, highlighted the higher implementation of capacity expansion registered in Italy in 2011 with 9 GW/year and that to reach the 2030 capacity target foreseen by 2019 PNIEC [26] it was necessary a constant 8.3 GW/year for the following 7 years [63]. Nowadays, with the 2024 PNIEC update, more than 10 GW/year of VRES installation are required.

Is there any coherence in the literature outcomes? Yes, the

research papers in the literature are largely aligned in terms of general technology-based outcomes, consistently repeating well-known concepts for the development of decarbonization strategies. Specifically, over the last decade, the works analyzed in the context of the Italian energy transition repeatedly present the same key ideas, with little more than incremental improvements in methodology or slight extensions of the analysis. While the content is robust, it lacks originality and offers no shocking insights or discoveries. The findings often feel repetitive and rehash familiar concepts, missing the opportunity to present truly novel or impactful results.

Are the research studies supporting the medium-term Italian policies strategy implementation? The literature review provides techno-economic insights in the context of the decarbonization process of the Italian energy system, although it is projected more in the long term, until 2050, rather than until 2030, which is what the policies at both European and Italian level are actually aiming at. From a thematic point of view, there is a correspondence between the academic insights and the strategies, such as the promotion of new green competitive technologies, the containment of GHGs emissions or the sector-coupling concept.

The decarbonization process requires relevant and burdensome changes and mutations of the Italian energy system, tailored to guarantee energy security and a green, sustainable and resilient economy. Although considerable efforts have been made in recent decades, particularly through EU directives setting targets and the Italian national plan, there remains a significant gap in achieving these targets. However, it has been clear from the outset which key measures should be pursued to address the issue.

Overall, this paper provides an overview of research and policies related to the decarbonization of the Italian energy system as a first step for future work. It establishes essential benchmarks for the analysis, facilitating the inclusion of new elements and greater detail. In particular, it emphasizes the need to extend the analysis beyond established findings by integrating more detailed technical characterizations and addressing real-world constraints, such as technical constraints on production capacity, economic barriers to investment, and practical challenges in constructing and deploying energy infrastructure. New approaches should not only provide strategic guidance, but also address these practical aspects of implementation. While the European Union provides common targets for all Member States, these frameworks often overlook the specific context of individual countries in terms of challenges and pressing issues. More targeted, vertical policies at the national level could better address these gaps. However, national policies that are actually internally provided, as well as the existing literature, fail to take into account the real constraints and implementation challenges that are crucial for a successful energy transition. Therefore, also policy guidance needs to integrate these practical realities to ensure a more effective and feasible transition.

ACKNOWLEDGMENT

Project funded under the National Recovery and Resilience Plan (NRRP), Italy, Mission 4 Component 2 Investment 1.3 - Call for tender No. 1561 of 11.10.2022 of Ministero dell'Università e della Ricerca (MUR) ; funded by the European Union – NextGenerationEU Award Number: Project code PE0000021, Concession Decree No. 1561 of 11.10.2022 adopted by Ministero dell'Università e della Ricerca (MUR), Italy, CUP, Italy E13C22001890001, Project title “Network 4 Energy Sustainable Transition – NEST”.

REFERENCES

- [1] Eurostat, “Shedding light on energy in the EU – 2023 edition,” https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Oil_and_petrolium_products_-_a_statistical_overview#Final_consumption_in_the_EU_and_in_the_Member_States, 2024.
- [2] European Commission, “GHG emissions of all world countries - Report 2024,” https://edgar.jrc.ec.europa.eu/report_2024#emissions_table, 2024.
- [3] R. A. Acevedo and M. Lorca-Susino, “The european union oil dependency: a threat to economic growth and diplomatic freedom,” *International Journal of Energy Sector Management*, vol. 15, no. 5, pp. 987–1006, 2021.
- [4] T. Rokicki, P. Bórawski, and A. Szeberényi, “The impact of the 2020–2022 crises on eu countries’ independence from energy imports, particularly from russia,” *Energies*, vol. 16, no. 18, p. 6629, 2023.
- [5] “Download Center,” <https://dati.terna.it/en/download-center>, Accessed 21/01/2025.
- [6] J. Cifuentes-Faura, “European union policies and their role in combating climate change over the years,” *Air Quality, Atmosphere & Health*, vol. 15, no. 8, pp. 1333–1340, 2022.
- [7] S. Strunz, E. Gawel, and P. Lehmann, “The political economy of renewable energy policies in germany and the eu,” *Utilities Policy*, vol. 42, pp. 33–41, 2016.
- [8] H. Wojtaszek, I. Miciuła, D. Modrzejewska, A. Stecyk, M. Sikora, A. Wójcik-Czerniawska, M. Smolarek, A. Kowalczyk, and M. Chojnacka, “Energy policy until 2050—comparative analysis between poland and germany,” *Energies*, vol. 17, no. 2, p. 421, 2024.
- [9] A. Carvalho, L. Schmidt, F. D. Santos, and A. Delicado, “Climate change research and policy in portugal,” *Wiley Interdisciplinary Reviews: Climate Change*, vol. 5, no. 2, pp. 199–217, 2014.
- [10] E. Zervas, L. Vatikiotis, Z. Gareiou, S. Manika, and R. Herrero-Martin, “Assessment of the greek national plan of energy and climate change—critical remarks,” *Sustainability*, vol. 13, no. 23, p. 13143, 2021.
- [11] C. Moscoloni, C. Carà, R. Novo, E. Giglio, G. Mattiazzo, *et al.*, “A comparison of the european regulatory framework for the deployment of offshore renewable energy project,” in *Proceedings of the European Wave and Tidal Energy Conference*, vol. 15, 2023.
- [12] “Kyoto Protocol,” https://unfccc.int/kyoto_protocol, 1997.
- [13] United Nations, “Paris Agreement,” in *The Paris Agreement*, 2015.
- [14] European Commission, “2020 climate & energy package,” <https://eur-lex.europa.eu/EN/legal-content/summary/2020-climate-and-energy-package.html>, 2009.
- [15] E. Parliament and Council, “Directive 2009/28/ec,” *Official Journal of the European Union*, 2009.
- [16] European Commission, “The EU Strategy on Adaptation to Climate Change,” https://climate.ec.europa.eu/document/download/ed34b40f-0408-4d9f-a8de-674ecc27ee4c_en?filename=eu_strategy_en.pdf, 2013.
- [17] European Commission, “Energy Union Strategy,” [https://www.europarl.europa.eu/RegData/etudes/BRIE/2015/551310/EPRS_BRI\(2015\)551310_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/BRIE/2015/551310/EPRS_BRI(2015)551310_EN.pdf), 2015.
- [18] Ministero dell’Ambiente e della Tutela del Territorio e del Mare, “Strategia Nazionale di Adattamento ai Cambiamenti Climatici,” https://www.mase.gov.it/sites/default/files/archivio/allegati/clima/documento_SNAC.pdf, 2015.
- [19] Ministero delle Imprese e del Made in Italy, “Strategia Energetica Nazionale,” <https://www.mimit.gov.it/images/stories/documenti/Te sto-integrale-SEN-2017.pdf>, 2017.
- [20] European Parliament and Council, “Directive 2018/2001/EU,” *Official Journal of the European Union*, 2018.
- [21] E. Parliament and Council, “Directive 2018/2002/eu,” *Official Journal of the European Union*, 2018.
- [22] European Parliament and Council, “Regulation (eu) 2018/1999,” *Official Journal of the European Union*, 2018.
- [23] Ministero dello Sviluppo Economico, Ministero dell’Ambiente e della Tutela del Territorio e del Mare, Ministero delle Infrastrutture e dei Trasporti, “Piano Nazionale Integrato per l’Energia e il Clima,” https://www.mase.gov.it/sites/default/files/archivio/proposta_di_piano_nazionale_integrato_per_energia_e_il_clima_italiano.pdf, 2018.
- [24] Consiglio dei Ministri, “Decreto-Legge Clima,” <https://www.mase.gov.it/comunicati/decreto-clima-un-primo-importante-passo-contrastare-i-cambiamenti-climatici#:~:text=1%20decreto%20interviene%20con%20misure%20urgenti%20in%20tutti,rilevanti%2C%20salute%20umana%2C%20suolo%20ed%20usi%20correlati%2C%20trasporti>, 2019.
- [25] European Commission, “European Green Deal,” https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_it, 2019.
- [26] Ministero dello Sviluppo Economico, Ministero dell’Ambiente e della Tutela del Territorio e del Mare, Ministero delle Infrastrutture e dei Trasporti, “Piano Nazionale integrato per l’Energia e il Clima,” https://www.mase.gov.it/sites/default/files/archivio/pniec_finale_17012020.pdf, 2019.
- [27] European Parliament and Council, “Regulation (EU) 2021/1119,” *Official Journal of the European Union*, 2021.
- [28] European Commission and Council, “The new EU Strategy on Adaptation to Climate Change,” <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021DC0082>, 2021.
- [29] European Commission, “REPowerEU,” <https://www.consilium.europa.eu/en/policies/repowereu/>, 2021.
- [30] European Parliament and Council, “Directive (EU) 2023/2413,” *Official Journal of the European Union*, 2023.
- [31] E. Parliament and Council, “Directive 2023/1791/eu,” *Official Journal of the European Union*, 2023.
- [32] Ministero dell’Ambiente e della Sicurezza Energetica, “Piano Nazionale di Adattamento ai Cambiamenti Climatici,” https://www.mase.gov.it/sites/default/files/PNACC_DOCUMENTO_DI_PIANO.pdf, 2023.
- [33] Ministero dell’Ambiente e della Sicurezza Energetica, “Piano Nazionale integrato per l’Energia e il Clima,” https://www.mase.gov.it/sites/default/files/PNIEC_2024_revfin_01072024.pdf, 2024.
- [34] E. Bompard, A. Botterud, S. Corgnati, T. Huang, M. Jafari, P. Leone, S. Mauro, G. Montesano, C. Papa, and F. Profumo, “An electricity triangle for energy transition: Application to italy,” *Applied Energy*, vol. 277, p. 115525, 2020.
- [35] E. M. Carlini, C. Gadaleta, M. Migliori, F. Ferretti, R. Vailati, A. Venturini, and C. Puglisi, “Cost-effective target capacity assessment in the energy transition: The italian methodology,” *Energies*, vol. 17, no. 12, p. 2824, 2024.
- [36] F. Gardumi, M. Welsch, M. Howells, and E. Colombo, “Representation of balancing options for variable renewables in long-term energy system models: An application to osemosys,” *Energies*, vol. 12, no. 12, p. 2366, 2019.
- [37] U. Giuliani, M. Agostini, C. Bustreo, and G. Zollino, “The fusion to hydrogen option in a carbon free energy system,” *IEEE Access*, vol. 11, pp. 131178–131190, 2023.
- [38] C. Cara, P. Marocco, R. Novo, M. Koivisto, M. Santarelli, and G. Mattiazzo, “Modeling the long-term evolution of the italian power sector: The role of renewable resources and energy storage facilities,” *International Journal of Hydrogen Energy*, vol. 59, pp. 1183–1195, 2024.
- [39] F. Lanati and M. Gaeta, “How to achieve a complete decarbonization of the italian energy system by 2050?,” in *2020 17th International Conference on the European Energy Market (EEM)*, pp. 1–5, IEEE, 2020.
- [40] M. Gaeta, C. Nsangwe Businge, and A. Gelmini, “Achieving net zero emissions in italy by 2050: challenges and opportunities,” *Energies*, vol. 15, no. 1, p. 46, 2021.
- [41] F. Calise, M. Dentice D’Accadia, C. Barletta, V. Battaglia, A. Pfeifer, and N. Duic, “Detailed modelling of the deep decarbonisation scenarios with demand response technologies in the heating and cooling sector: A case study for italy,” *Energies*, vol. 10, no. 10, p. 1535, 2017.
- [42] M. Jafari, E. Bompard, C. Delmastro, A. Botterud, and D. Grosso, “Electrify italy: The role of renewable energy,” *Gas*, vol. 2030, p. 2050, 2022.

- [43] A. Di Bella, F. Canti, M. G. Prina, V. Casalicchio, G. Manzolini, and W. Sparber, "Power system investment optimization to identify carbon neutrality scenarios for italy," *Environmental Research: Energy*, vol. 1, no. 3, p. 035001, 2024.
- [44] P. Colbertaldo, G. Guandalini, and S. Campanari, "Modelling the integrated power and transport energy system: The role of power-to-gas and hydrogen in long-term scenarios for italy," *Energy*, vol. 154, pp. 592–601, 2018.
- [45] P. Colbertaldo, S. Cerniauskas, T. Grube, M. Robinius, D. Stolten, and S. Campanari, "Clean mobility infrastructure and sector integration in long-term energy scenarios: The case of italy," *Renewable and Sustainable Energy Reviews*, vol. 133, p. 110086, 2020.
- [46] M. G. Prina, M. Lionetti, G. Manzolini, W. Sparber, and D. Moser, "Transition pathways optimization methodology through energyplan software for long-term energy planning," *Applied Energy*, vol. 235, pp. 356–368, 2019.
- [47] G. Colucci, D. Lerede, M. Nicoli, and L. Savoldi, "A dynamic accounting method for co2 emissions to assess the penetration of low-carbon fuels: application to the temoa-italy energy system optimization model," *Applied Energy*, vol. 352, p. 121951, 2023.
- [48] I. Henke, A. Carteni, C. Beatrice, D. Di Domenico, V. Marzano, S. M. Patella, M. Picone, D. Tocchi, and E. Cascetta, "Fit for 2030? possible scenarios of road transport demand, energy consumption and greenhouse gas emissions for italy," *Transport Policy*, vol. 159, pp. 67–82, 2024.
- [49] F. Onori, T. Milletti, M. Rossi, and G. Comodi, "Towards the target of the renewable energy directive (red) iii using photovoltaic and batteries: The case study of italy," in *Journal of Physics: Conference Series*, vol. 2893, p. 012004, IOP Publishing, 2024.
- [50] P. Colbertaldo, F. Parolin, and S. Campanari, "A comprehensive multi-node multi-vector multi-sector modelling framework to investigate integrated energy systems and assess decarbonisation needs," *Energy Conversion and Management*, vol. 291, p. 117168, 2023.
- [51] M. Borasio and S. Moret, "Deep decarbonisation of regional energy systems: A novel modelling approach and its application to the italian energy transition," *Renewable and Sustainable Energy Reviews*, vol. 153, p. 111730, 2022.
- [52] L. M. Pastore, D. Groppi, F. Feijoo, G. L. Basso, D. A. Garcia, and L. de Santoli, "Optimal decarbonisation pathways for the italian energy system: Modelling a long-term energy transition to achieve zero emission by 2050," *Applied Energy*, vol. 367, p. 123358, 2024.
- [53] F. Lombardi, B. Pickering, E. Colombo, and S. Pfenniger, "Policy decision support for renewables deployment through spatially explicit practically optimal alternatives," *Joule*, vol. 4, no. 10, pp. 2185–2207, 2020.
- [54] M. R. Di Nucci and A. Prontera, "The Italian energy transition in a multilevel system: between reinforcing dynamics and institutional constraints," *Zeitschrift für Politikwissenschaft*, vol. 33, no. 2, pp. 181–204, 2023.
- [55] M. Vellini, S. Bellocchi, M. Gambini, M. Manno, and T. Stilo, "Impact and costs of proposed scenarios for power sector decarbonisation: An italian case study," *Journal of Cleaner Production*, vol. 274, p. 123667, 2020.
- [56] S. Bellocchi, P. Colbertaldo, M. Manno, and B. Nastasi, "Assessing the effectiveness of hydrogen pathways: A techno-economic optimisation within an integrated energy system," *Energy*, vol. 263, p. 126017, 2023.
- [57] L. M. Pastore, G. L. Basso, L. Cristiani, and L. de Santoli, "Rising targets to 55% ghg emissions reduction—the smart energy systems approach for improving the italian energy strategy," *Energy*, vol. 259, p. 125049, 2022.
- [58] M. Jafari, M. Korpås, and A. Botterud, "Power system decarbonization: Impacts of energy storage duration and interannual renewables variability," *Renewable Energy*, vol. 156, pp. 1171–1185, 2020.
- [59] S. Bellocchi, M. De Falco, M. Gambini, M. Manno, T. Stilo, and M. Vellini, "Opportunities for power-to-gas and power-to-liquid in co2-reduced energy scenarios: The italian case," *Energy*, vol. 175, pp. 847–861, 2019.
- [60] S. Bellocchi, M. Manno, M. Noussan, M. G. Prina, and M. Vellini, "Electrification of transport and residential heating sectors in support of renewable penetration: Scenarios for the italian energy system," *Energy*, vol. 196, p. 117062, 2020.
- [61] S. Bellocchi, M. Gambini, M. Manno, T. Stilo, and M. Vellini, "Positive interactions between electric vehicles and renewable energy sources in co2-reduced energy scenarios: The italian case," *Energy*, vol. 161, pp. 172–182, 2018.
- [62] E. De Luca, A. Zini, O. Amerighi, G. Coletta, M. G. Oteri, L. G. Giuffrida, and G. Graditi, "A technology evaluation method for assessing the potential contribution of energy technologies to decarbonisation of the italian production system," *International Journal of Sustainable Energy Planning and Management*, vol. 29, pp. 41–56, 2020.
- [63] A. Sorce, A. Vannoni, D. Bellotti, and M. Rivarolo, "Environmental and economic assessment of the italian energy transition scenarios," in *Journal of Physics: Conference Series*, vol. 2648, p. 012090, IOP Publishing, 2023.
- [64] V. Andreoni, "Estimating the european co2 emissions change due to covid-19 restrictions," *Science of the Total Environment*, vol. 769, p. 145115, 2021.

APPENDIX

This section presents a detailed critical analysis of EU policies and Italian strategies on climate change and energy transition. The aim is to provide data, illustrating the evolution of the main target categories identified for the decarbonization process. Section A highlights the gaps between the current situation and the objectives outlined in the transition strategies. Section B overviews supporting Italian strategies provided by specific technical figures in the Italian energy field.

A. Detailed analysis of European and Italian targets and plans

Following the main plans overview offered in section II, both EU GHGs emissions and RES share trends are analyzed. Figure A.1(a) shows the variation of net CO₂ equivalent emissions rates in the EU from 1990, the reference year, to nowadays, varying with a decrescent trend. Since 2009, when the Climate and Energy Package 20-20-20 is outlined, the net CO₂-eqv emissions faced one of the sharpest fall from 3.8 billion tonnes to 3.1 billion tonnes in 2020, with a 19% reduction in less than 15 years, though largely influenced by the magnitude of the COVID-19 impacts rather than characterized by a sharper change in the behavior and management of the main polluting sectors [64]. Indeed, since 2015 when for the first time the 2030 is selected as mid-term target year, there is no evidence for an actual implementation of policies able to yearly get close the target. Considering the last tracked value of 2022 CO₂ net equivalent emissions level of 3.2 billion tonnes (higher than 2020), a further 35% reduction in GHGs is needed to achieve the 55% decrease by 2030, as foreseen since 2018. Considering the RES share in energy consumption, an increase has been registered, rising from 12.5% in 2010 to 24.5% in 2023 [30]. The highest contributions come from Sweden (66.4%), Finland (50.8%), and Denmark (44.9%), which are able to leverage their favorable potential in renewable sources (i.e. hydro-power, onshore and offshore wind). On the other hand, countries where RES penetration still represents a major challenge include Luxembourg (11.6%) and Malta (15.7%). Figure A.1(b) shows the last 10 years evolution of the RES share in the EU from 2014 to 2023, showing the distance to the 2030 target, which requires further efforts quantified in a 73% divergence.

Moreover, considering the Italian plans, three main strategies have been outlined in the last two decades (2017 SEN, 2019 PNIEC, 2024 PNIEC), suggesting tailor-made Italian targets to achieve decarbonization and adaptation to climate change. It is interesting to note that the strategic framework

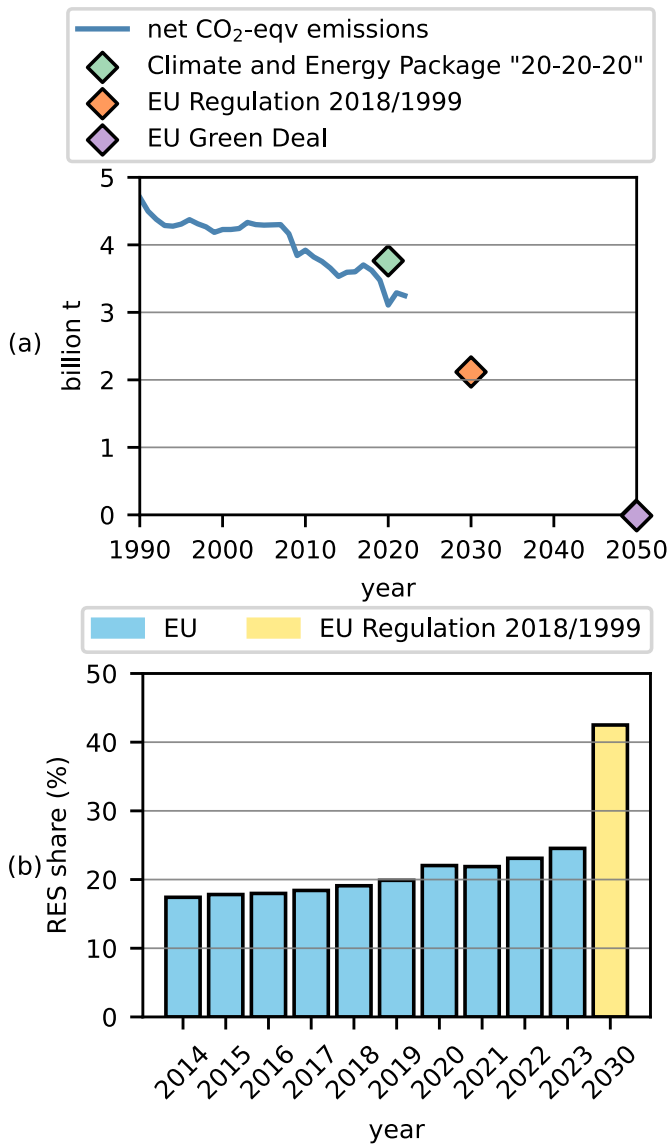


Fig. A.1: (a) European Union net CO₂ equivalent emissions; (b) European Union share of energy from renewable sources.

remains the same between the two versions of the PNIEC, with updates related to the specific actions. For instance, considering the PNIEC targets for the electricity sector from 2019 to 2024, i.e. in 5 years, the growth target for the RES deployment has been significantly increased. Specifically, the 2030 capacity targets in the 2024 PNIEC compared to the 2019 PNIEC have been more than doubled for PV (+55% from 51.1 GW to 79.2 GW) and increased by more than a third for OW (+42% from 18.4 GW to 26.0 GW). The overall VRES capacity increase foreseen by 2030 is around 107 GW, also including offshore wind and concentrated solar technologies still not present in the Italian energy mix, which compared to the 42 GW in 2023 requires an average yearly capacity increase equal to 18 GW/year: the higher maximum capacity increase in Italy has been equal to around 9 GW/year in 2011 [63]. On

the other hand, other Italian targets, such as the carbon phase-out, have been postponed from 2019 to 2024 PNIEC. Indeed, since 2017 with SEN [19] and then reconfirmed in 2019 PNIEC [26], the coal phase-out was foreseen until 2025, but taking into account the limitation and ensuring its replacement with specific plans and infrastructures, promoting renewable energy and energy efficiency measures. In 2024, considering the corresponding benefits and the subsequent criticalities that occurred (i.e. gas crisis due to the Ukrainian-Russian conflict), the carbon phase-out process is redesigned, taking into account a gradual decommissioning of carbon-based plants by 2026 (except for the island of Sardinia, where the process is expected to be completed by 2028). Furthermore, in order to diversify the electricity mix, nuclear technology is included as a possible clean technology that can support the achievement of climate neutrality and provide greater energy security due to its dispatchable nature and limited vulnerability and raw material dependence. Finally, another significant change is the share of gross final consumption supplied by RES, which is set at 30% in 2019 PNIEC by 2030 and 39.4% in 2024 PNIEC, representing an ambitious annual increase of around 2-3 percentage points from 2019 up to 2030.

B. Key players in the Italian energy context

In the development of medium- long-term strategies, there are some key players, often assisting Italian ministries in the development of national strategic plans, namely *Gestore dei Servizi Energetici* (GSE), *Ricerca sul Sistema Energetico* (RSE) and Terna. GSE, a company regulated by the Ministry of Economy and Finance, manages and promotes energy services in Italy, supporting the country's energy transition. RSE is a company regulated by GSE that works in the field of research and supports the development of the energy sectors, in particular in the elaboration of strategic national projects. Finally, Terna is the main and only Transmission System Operator (TSO) in Italy, capable of managing the electricity network and also involved in the energy transition commitment to ensure the penetration of RES. In particular, Terna proposes, also in collaboration with other entities, such as Snam (*Società Nazionale Metanodotti*), a series of development plans starting from 2019, elaborating new long-term scenarios that outline the decarbonization process.

In particular, among the various studies delivered, there is the "*Documento di Descrizione degli Scenari*" (DDS) in 2018, then subsequently updated for the years 2019, 2022 and 2024, and the "*Piano di Sviluppo*" (PdS) in 2020. Along the different reports, there are different typologies of contrasting development scenarios, defined taking into account the ongoing national and European policies. For example, in the 2019 DDS, two main development scenarios are deepened: the CEN (Centralized) and the DEC (Decentralized), both achieving the 2030 decarbonization targets, RES share, energy efficiency and CO₂ emission limits, optimizing the overall energy mix (cost minimization). Besides, a reference scenario by 2030 is build considering the first proposal version of the 2019 PNIEC [23], assuming its targets in term of energy efficiency, RES

target year	technology	MISE MATTM MIT		MASE		Terna								
		PNIEC 2019	PNIEC 2024	DDS 2019			PdS 2020		DDS 2022			DDS 2024		
-	(GW)			CEN	DEC	PNIEC	CEN	DEC	LT	FF55	PNIEC slow			
2030	PV	51.1	79.173	30.5	49.3	50.9	38	49	51.1	74.5	71			
	CSP	0.9	0.08						0.9	0.9				
	onshore wind	18.4	26.04	13.6	18.9	18.4	17	19	18.4	18.4	22			
	offshore wind	0.9	2.1						0.9	8.5				
2040	(GW)			CEN	DEC		CEN	DEC	DE	GA	LT	DE	GA	PNIEC slow
	PV			50.6	69.8		51	70	114	102	75	121	111	105
	CSP													
	onshore wind			22.1	25.4		22	25	42	39	28	49	43	39
	offshore wind													

TABLE A.1: Summary of target technologies capacity for the power sector only, outlined in 2019 and 2024 PNIECs, and in Terna mid- long- term scenarios (CEN: Centralized, DEC: Decentralized, LT (Late Transition): aligned with the National Trend Italia scenario for the final uses consumption, green gas development, but for the RES considers a different allocation accounting the connection requests received by Terna; FF55 (Fit for 55): achieves the EU GHGs targets by means of electrification strategies and RES increase; GA (Global Transition): GHGs target achieved by means of energy consumption containment, RES development, CO₂ technologies; DE (Distributed Energy): GHGs target achieved by means of electricity vector deployment with RES, storage facilities, electrolyzers to cope with overgeneration, CO₂ technologies; PNIEC slow: considers a delay in the achievement of PNIEC measures due to a slower implementation of the different measures, such as electrification, RES deployment and green fuels.)

share and GHGs emissions. Although the macro-economic context is the same for both the elaborated scenarios, different boundary conditions are considered to reach the 2030 targets: the CEN assumes that the 2030 targets will be reached by limiting energy consumption and developing RES, relying heavily on the use of green gas; the DEC hypothesizes a more rapid development of the electricity vector and RES, relying heavily on VRES, with the associated investment requirements. Moreover for instance, the 2024 DDS presents a differentiated set of scenarios, taking into account the 2024 PNIEC policy with various levels of implementation and the plans of the ENTSO-Es' (European Network of Transmission System Operators for Electricity). Table A.1 summaries the main outcomes.

Figure A.2 shows for the 2030 target year, for the different strategies defined in the PNIECs and in the Terna deliverables, the foreseen capacities increase related to PV and OW technologies with respect to the actual installed capacity in 2019 [5], assumed here as a reference year. According to the different plans and strategies, and also taking into account the variable context, these scenario results, which actually depend on the initial assumptions considered, consist in the foreseen capacity increase. Specifically, from 2019 to 2023 in Italy, there has been an increase in installed RES capacity of 45% for PV (from 21 GW to 30 GW) and of 15% for OW (from 11 GW to 12 GW) technologies (horizontal lines in Figure A.2). Nevertheless, the simulated scenarios require at least about 50% of the capacity increase for PV technology, up to 280% increase as foreseen in the 2024 PNIEC (+161% considering the total installed capacity of 30.3 GW in 2023), and for OW technology at least 27% capacity increase is required by the 2024 PNIEC, which therefore embodies the most ambitious target strategy (+121% considering the total installed capacity of 30.3 GW in 2023). It should also be stressed that the differences between the results of the different scenarios are

due to the constant variation in the socio-economic framework and the annual updating of energy and environmental policies, particularly at national level, and the related assumption parameters such as facilities costs and resource potential. Despite their volatility, these results are useful to provide insights into possible feasible pathways, highlighting certainly unavoidable key choices to advance decarbonization and energy system transformation.

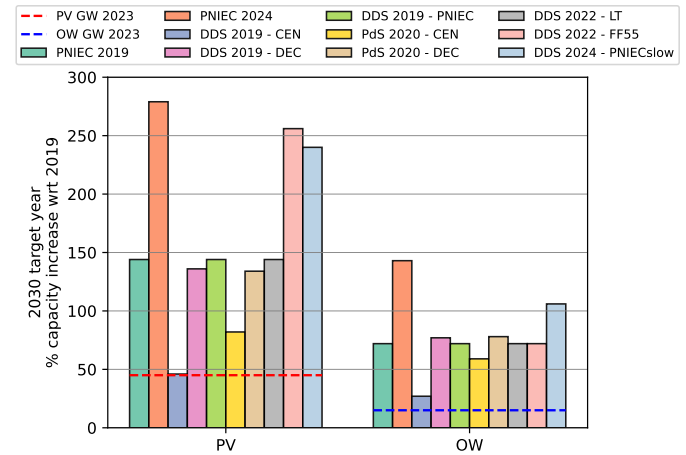


Fig. A.2: Percentage target capacity increase with respect to 2019 actual installed capacity in Italy for the main scenarios outlined in Terna DDSs and PdS.

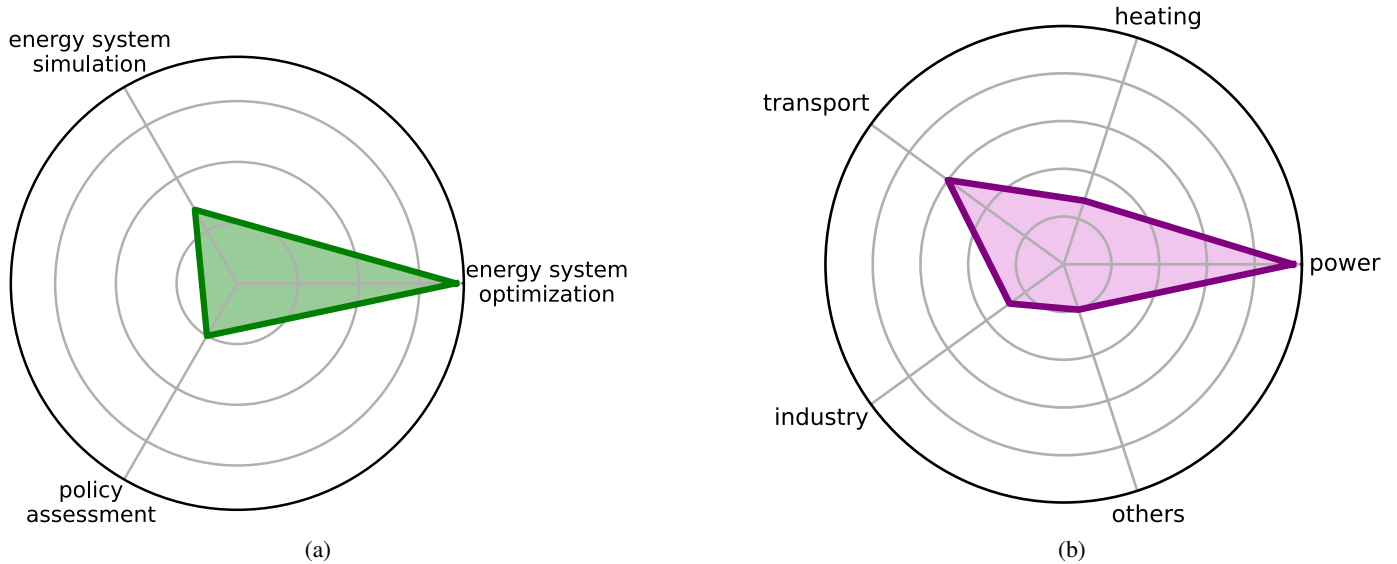


Fig. A.3: (a) Representation of the identified methodologies in literature research papers; (b) Radar plots of identified methodologies and sectors for decarbonization.

Ref.	Italy	European Union	Year	Target year	Main targets
[14], [15]		Climate and Energy Package "20-20-20" RED I 2009/28/EC	2009	2020	-20% GHGs +20% RES +20% EE
[16]		European Strategy on Adaptation to climate change	2013		
[17]		Energy Union Strategy	2015	2030	-40% GHGs +27% RES +30% EE +15% EI
[18]	Strategia nazionale di adattamento ai cambiamenti climatici (SNAC)		2015	2050	-80/90% GHGs
[19]	Strategia Energetica Nazionale (SEN)		2017		
[21]		European Directive 2018/2002	2018	2030	-32.5% EC
[20]		RED II 2018/2001/EC	2018	2030	+32% RES
[22]		European Regulation 2018/1999	2018	2030	-55% GHGs +42.5% RES -11.7% EC
[23]	PNIEC proposal		2018		-90% GHGs
[24]	Decreto Clima		2019		
[25]		European Green Deal	2019	2050	net Carbon neutral
[26]	Piano Nazionale Integrato per l'Energia e il Clima (PNIEC)		2019		
[7]		European Fit for 55	2021	2030	-55% GHGs
[27]		European Climate Law	2021	2030	-55% GHGs
[28]		European Adaptation Strategy	2021		
[29]		REPowerEU	2022	2025 2030	320 GW PV 600 GW PV
[30]		RED III 2023/2413/EC	2023	2030	+42.5% RES
[31]		EU Directive 2023/1791	2023	2030	-11.7% EC
[32]	Piano Nazionale di Adattamento ai Cambiamenti Climatici (PNACC)		2023		
[33]	Piano Nazionale Integrato per l'Energia e il Clima (PNIEC)		2024		

TABLE A.2: Summary table tracking the main European and Italian targets, plan and strategies in the last 15 years.

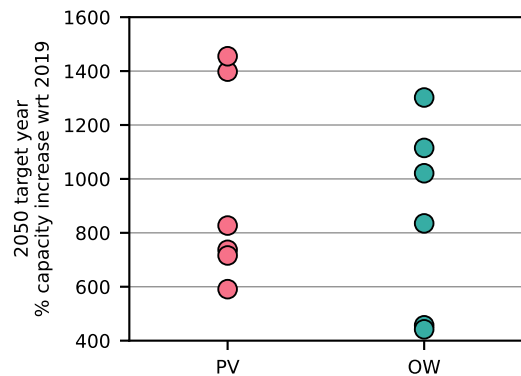


Fig. A.4: PV and OW capacity outcomes percentage difference, compared to 2019 installed capacity, of the selected subset of papers [50]–[53], characterized by the following common features: power, heating and transport sectors included in the energy system; hourly resolution; multi-nodal; full decarbonization target by 2050; single-year analysis.

Nomenclature	
DDS	Documento di Descrizione degli Scenari
EC	Energy Consumption
EE	Energy Efficiency
EI	Electricity Interconnection
GHGs	Green House Gases
MASE	Ministero dell'Ambiente e della Sicurezza Energetica
MATTM	Ministero dell'Ambiente e della Tutela del Territorio e del Mare
MISE	Ministero dello Sviluppo Economico
MIT	Ministero delle Infrastrutture e dei Trasporti
OW	Onshore wind technology
PdS	Piano di Sviluppo
PV	Photovoltaic technology
PNIEC	Piano Nazionale Integrato per l'Energia e il Clima
RES	Renewable Energy Sources
VRES	Variable Renewable Energy Sources

Ref.	Year	Tool	Objective function			Spatial resolution		Time horizon		Target year			Temporal resolution	Energy sectors					
			single	multi	type	one node	multi-node	single year	multi-year	2030	2040	2050		power	heating	transport	industry	others	
[41]	2017	EnergyPLAN						x				x	h		x				
[44]	2018						x	x				x	h	x		x			
[61]	2018	EnergyPLAN																	
[46]	2019	EPLANoptTP		x	<i>min</i> CO ₂ &Costs	x			x	x	x	x	h	x					
[36]	2019	OSeMOSYS	x		<i>min</i> Cost	x			x	x	x		16 TS	x					
[59]	2019	EnergyPLAN											h	x		x			
[34]	2020	GenX	x		<i>min</i> Cost			x				x	h	x			x		x
[60]	2020	EnergyPLAN		x	<i>min</i> CO ₂ &Costs			x					h		x	x			
[58]	2020	GenX	x		Cost	x		x				x	h	x					
[53]	2020	Calliope	x		<i>min</i> Cost		x	x				x	h	x	x	x			
[39]	2020	TIMES	x		<i>min</i> Cost	x		x				x	12 TS	x		x	x		x
[45]	2020		x		<i>max</i> RES		x	x				x	h	x		x			
[62]	2020																		
[55]	2020									x				x					
[40]	2021	TIMES-RSE, sMTISIM	x		<i>min</i> Cost								12 TS	x		x	x		x
[51]	2022	EnergyScope	x		<i>min</i> Cost		x	x				x	12 TS	x	x	x			
[57]	2022	EnergyPLAN, MAT4EnergyPLAN		x	<i>min</i> CO ₂ &Costs	x		x					h	x	x	x	x		
[42]	2022	GenX	x		<i>min</i> Cost	x		x		x		x	h	x					
[50]	2023	OMNI-ES	x		<i>min</i> Cost		x	x				x	h	x	x	x	x		x
[56]	2023	EnergyPLAN		x	<i>min</i> CO ₂ &Costs			x				x	h	x		x			
[37]	2023	COMESE	x		<i>min</i> LCOE		x	x					h						
[47]	2023	TEMOA							x	x	x			x		x	x		x
[63]	2023									x				x					
[54]	2023																		
[52]	2024	H2RES	x		<i>min</i> Cost	x			x	x	x		h	x	x	x	x		x
[38]	2024	OSeMOSYS	x		<i>min</i> Cost	x			x	x	x		30 TS	x					
[43]	2024	Oemof			<i>min</i> Cost		x	x					h	x					
[49]	2024	BESS																	
[48]	2024							x									x		
[35]	2024	transmission expansion model					x	x					h	x			x		

TABLE A.3: Summary table of the literature papers analyzed, highlighting key methodology details, such as tool used, type of objective function adopted (*min* Cost: total system cost minimization, *min* CO₂&Costs: total system cost and CO₂ emissions minimization, *min* LCOE: Levelized Cost of Energy minimization, *max* RES: RES surplus use maximization), spatial and temporal resolution (h: hourly, TS: time-slice), target year, and energy sectors included.