Assessing the role of storage and thermoelectric plants in the energy transition: a short- and medium-term scenario analysis with Italy as a case study

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Assessing the role of storage and thermoelectric plants in the energy transition: a short- and medium-term scenario analysis with Italy as a case study

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A B S T R A C T

Global warming is pushing many countries worldwide to adopt decarbonization strategies aimed at reducing the dependence on fossil fuels. The successful development of these strategies critically depends on the ability to model and evaluate alternative options, thereby enabling policymakers to identify and implement the most effective solutions. In this context, the present study introduces a detailed operational analysis of the Italian energy system under the 2030 and 2040 horizons, based on authoritative scenarios developed by national transmission system operators. The primary goal is to complement these scenarios by highlighting short- and medium-term operational challenges, particularly concerning the role of thermoelectric power plants and electricity storage systems. To this aim, a set of key performance indicators is introduced to systematically assess scenario impacts. The analysis captures the effects of rising electricity demand, driven by the diffusion of electric vehicles and heat pumps, on system operation, highlighting a projected 25% increase in peak demand along with an 8.3% increase in peak thermoelectric generation. Despite a marked decline in the capacity factor of thermoelectric power plants (from 0.54 to 0.18), these units remain essential to meet demand during extended periods of low renewable generation, with peak capacity requirements remaining close to 40 GW. The results also underscore the role of electricity storage in providing short-term flexibility. However, the benefits of additional storage become marginal beyond 230 GWh of capacity.

1. Introduction

The European Climate Law, officially adopted in July 2021, specifically writes into law the goals set out in the European Green Deal, whose aim is climate neutrality by 2050, meaning the achievement of net zero greenhouse gas (GHG) emissions. Ambitious intermediate goals have been set for the Members to achieve and measures to properly keep track of progress have been included. The first intermediate goal set is the reduction of 55% of net GHG emissions with respect to the 1990 levels by 2030 [1]. To reach such ambitious targets, a set of coherent actions and policies need to be developed and properly implemented. Existing studies evaluate potential scenarios and narratives that could support an evolution of the current energy system towards a zero-carbon configuration.

The Ten-Year Network Development Plan 2022 (TYNDP22) is an updated gas and electricity joint scenario report and is the result of the collaboration of the European Network Transmission System Operators both for Gas and Electricity (ENTSO-G and ENTSO-E) [2]. Its aim is to present robust scenarios fully compliant with the Paris Agreement and with the European ambitions for achieving carbon neutrality by 2050. In general, scenarios are pictures of possible futures under certain circumstances that must be defined, and not a forecast of what the future may look like; they enable investment planning in infrastructure while providing insights into the evolution of integrated energy systems. The TYNDP22 has been redacted with the participation of numerous stakeholders from a wide range of industries and sectors, non-governmental organization (NGOs), National Regulatory Authorities and Member states to increase the quality and reliability of the data on which the scenarios are based and therefore of the results obtained from said scenarios.

Based on the guidelines provided by the ENTSOs, the Italian transmission system operators (TSOs) for electricity and gas, namely Terna

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Table 1
Overview of studies on the Italian energy transition.

Source	Simulation tool	Horizon	RES share in electricity consumption	Aim
Calise et al. (2017) [21]	EnergyPLAN and TRNSYS	2050	80%–90%	80 % GHG reduction
Bellocchi et al. (2018) [24]	EnergyPLAN	Unstated	60%	Analysis of electrification of the transport sector
Bellocchi et al. (2019) [23]	EnergyPLAN	2030, 2050	Up to 65%	Analysis of benefits of transport electrification and storage utilization
Bellocchi et al. (2020) [18]	EnergyPLAN	Unstated	Up to 65%	Analysis of electrification of transport and building sectors
Pastore et al. (2022) [38]	EnergyPLAN	2030	55%–75%[a]	Build a scenario reaching 55 % GHG reduction
Cerruti et al. (2023) [26]	EnergyPLAN	2030 and 2040	60%[a]	Assessment of the electrification of the transport sector
Magnolia et al. (2023) [29]	EnergyPLAN	2030	Higher than 55%	Build an optimal scenario coherent with NECP targets
Bellocchi et al. (2023) [28]	EnergyPLAN	2030 and 2050	55%[a] (2030), 65%[a] (2050)	Techno-economic optimization for hydrogen pathways
Sgaramella et al. (2023) [39]	EnergyPLAN	2030	55%–75%[a]	Matching RES integration to Italian hydrogen strategy requirements
Carà et al. (2024) [40]	Osemosys	2020–2050 *(1 year step)*	Up to 95% (2050)	Study on the utilization of battery and hydrogen storage (for power sector) in supporting RES expansion
Nicoli et al. (2024) [41]	TEMOA	2030, 2040, 2050	Up to 59% (2030), 74% (2040) and 80% (2050).	Evaluate the effect of storage on long-term energy planning
Pastore et al. (2024) [42]	EnergyPLAN	2050	100%	Build an optimal scenario for 100% RES energy system
Pastore et al. (2025) [31]	H2RES	2020–2050 *(5 years step)*	100%	Build an optimal scenario for 100% RES energy system
Pastore et al. (2025) [32]	EnergyPLAN	2050	100%	Socio-economic implications of decarbonizing the system
Present work	**EnergyPLAN**	**2030 and 2040**	**Up to 65% (2030), 78% (2040)**	**Evaluation of the hourly contribution of thermoelectric plants and storage to grid balancing**

[a] This value is not explicitly defined in the original references. The value reported in the table has been estimated by the authors based on the information available in the cited reference.

and SNAM respectively, have developed analogous but more detailed national scenarios using their extensive knowledge of the national infrastructure. These scenarios reflect the specific characteristics of the Italian energy system and are described in the “Documento di Descrizione degli Scenari 2022” [3]. The Distributed Energy (DE) scenario represents an energy system leaning towards autonomy, using decentralized technologies such as photovoltaics (PV) and small storages, and maximizing the utilization of renewable energy sources (RES) and the integration of smart systems. On the other hand, the Global Ambition (GA) scenario pursues the decarbonization of the energy supply through electrification and the utilization of low carbon solutions; a centralized approach is here used using large scale technologies such as wind farms and large storages. The FF55 is an intermediate scenario in 2030 that presents elements of both DE and GA scenarios [3].

These scenarios compare alternative short- and medium-term solutions towards a pathway that aims at reaching zero-carbon emissions by 2050. The deployment of these technologies and solutions will require specific actions in policies and in market rules to properly dispatch flexibility options to compensate for the variability of renewable sources.

1.1. Literature review

Planning in energy systems has risen in priority as the transition towards greener systems is perceived as essential. To support this shift, various tools and methodologies have been developed, as comprehensively outlined in Ref. [4], where their key characteristics are highlighted. Among them, one of the most widely used is EnergyPLAN [5], which is based on the smart energy system (SES) approach, as defined by Lund et al. in Ref. [6] and built on the principle of leveraging existing synergies between energy sectors. EnergyPLAN facilitates the simulation and analysis of energy systems within this framework. This tool has been extensively utilized in case studies of varying scales, fostering the development of a comprehensive body of research on energy transition pathways towards 100% renewable systems [7,8]. The scenarios analyzed vary from municipal (Zagreb [9], Copenhagen [10], Aalborg [11]), to regional (Northern Ireland [12], Guayas [13], Sichuan [14]), national (Chile [15], Germany [16], Portugal [17], Italy [18]) and multi-national (Europe [19], Latin America and the Caribbean [20]) scales.

Concerning Italian energy system, Table 1 summarizes a selection of scenario-based studies analyzing its future evolution. These works differ in terms of methodological approaches, time horizons, end-use sectors considered, and energy vectors involved. The Italian energy system has in fact been object of many studies focusing on different aspects of the problem, such as the electrification of the heating and transport sectors driven by the diffusion of heat pumps [21,22] and electric vehicles (EVs) [23–26]. Results suggest that increasing the share of heat pumps and EVs leads to CO_2 emissions reduction even if the renewable share is relatively low, due to the high efficiency of gas fired power plants and the inherent efficiency of heat pumps and EVs. The role of hydrogen in linking heat and electricity in SES has been studied by Nastasi et al. [27] and detailed for the Italian energy system by Bellocchi et al. [28] and Magnolia et al. [29]. Hydrogen and electrofuels are expected to partially replace both natural gas in the gas grid and diesel fuel in heavy transport leading to a reduction in CO_2 emissions.

Due to the increase in distributed power generation and electricity intensive processes, the coordinated development of the electricity grid is also essential to increase the resilience of the system itself [30]. Other works, such as those by Pastore et al. [31,32], pushed the boundaries of energy modelling towards 100% renewable energy systems highlighting optimal solutions for achieving complete reliance on renewable energy sources, using 2050 as a target year.

Nevertheless, studies have also shown that, while moving towards these long-term goals, the increasing production from renewable sources and the electrification of energy consumption will significantly alter the utilization patterns of major power plants [33,34] and increase the importance of storage [35,36]. For instance, Schill et al. [37] showed that a high share of RES, specifically a scenario with 50% RES penetration for the German power system, leads to an increased number of startups and associated operational costs for conventional power plants, although storage can partially alleviate these impacts. These effects are worth studying also for the Italian case in a transition phase to understand the consequences of increased RES integration on the flexibility requirements and operational stress of conventional units.

1.2. Scope of the work

In this context, the present work aims to reinforce and extend the existing literature by conducting a detailed hourly-resolution analysis of thermoelectric plant behavior in the short and medium term. Focusing on the Italian energy system as a case study, it explores how the interaction between intermittent RES and storage systems affects the operation and utilization of thermoelectric assets, resources that remain essential for maintaining grid stability during the energy transition. To the best of the authors' knowledge, current research offers only limited insights at this level of temporal granularity and national specificity, making this study a relevant contribution to the ongoing discourse. This study specifically addresses this gap by:

- Conducting an extensive hourly analysis of the Italian national energy system, based on scenarios developed by TSOs in collaboration with European stakeholders and tailored for Italy, by employing EnergyPLAN to simulate both the current system and projections for 2030 and 2040. The ultimate aim is to complement and reinforce the national scenarios by providing a detailed operational perspective.
- Focusing particularly on operational dynamics of thermoelectric power plants and electricity storage under high variability from intermittent RES (iRES) and fluctuating electricity demand profiles.
- Investigating the influence of demand shape variations on the performance and operational roles of thermoelectric power plants and electricity storage, with a focus on relevant key performance indicators (KPIs) such as capacity factors, peak power output, and net load variability. This allows for a critical assessment of their capability to ensure flexibility and stability in future energy systems.

The paper is structured as follows: Section 2 outlines the methodology, encompassing the models for energy demand and production; Section 3 presents the results and Section 4 summarizes the conclusions drawn from the study.

2. Methodology

The layout of the complete model is presented in Fig. 1. A great effort has been made to collect all the data needed to make significant analysis of the system in EnergyPLAN, from the energy demands of each sector and their hourly profiles to the technologies employed in each scenario. The sectors taken into account are the civil sector, consisting of the residential, commercial and service sectors, industry and transport. Other sectors, whose impact on the total final consumption is only marginal, such as agriculture, forestry and fishing, have been aggregated. The output of the models realized in the simulation tool is essentially an hourly balance of the energy system considering all the energy demands and vectors. The layout of the complete model is presented in Fig. 1.

The association representing the European National Transmission System Operators (ENTSOs) published during 2022 the Ten-Year Network Development Plan in which two new scenarios are presented: the Distributed Energy (DE) scenario and the Global Ambition (GA) scenario. The purpose of the two scenarios is to explore and cover the uncertainty in the decarbonization of the energy system for the years 2030 and 2040 [2,43]. Both scenarios aim actively at achieving carbon neutrality by 2050 and 55% CO_2 emission reduction by 2030 with respect to the 1990 levels as per the European Climate Law (2021). The DE scenario assumes that authorities will incentivize the decentralization of the energy system through local initiatives of citizens, communities and businesses. On the other hand, the Global Ambition scenario hypothesizes the development of a wide range of low-carbon technologies, many of which are centralized, to carry on the decarbonization; in this scenario the international exchange of energy is essential, especially hydrogen. Therefore, the GA scenario is less dependent on the electric vector and willing to explore the effectiveness of other renewable vectors, namely biomethane and green hydrogen. Both scenarios assume a significant increase in the efficiency of the end-use sectors, especially the civil sector, through building renovations.

The Italian TSOs (SNAM and Terna) adapted the ENTSOs indications to the Italian energy system specifically and redacted the "*Documento di Descrizione degli Scenari 2022*" (DDS22) where more accurate forecasts are reported [3]; also, the 2030 scenarios have been unified realizing only one intermediate scenario called Fit for 55 (FF55) owning elements of both DE and GA.

Since these documents give a quite complete picture of the future energy consumption, they are good to be analyzed through a simulation tool; however, there still are some missing data and other reports have been used. In general, to run simulations over future energy systems, the choice of coherent weather parameters is fundamental and the average climatic year chosen for the analysis of the scenarios is 2010 [44].

Since the main aim of this work is to study the impact of intermittent renewable generation on the electric system, the focus during the model building has been on electricity demand and supply, considering all the

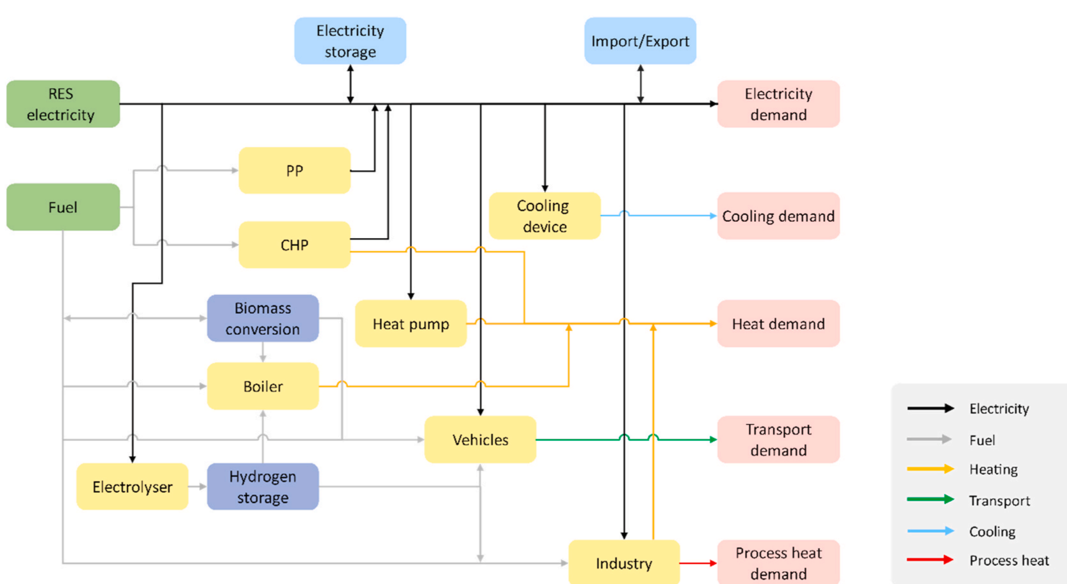

Fig. 1. Operating scheme of the main elements used in EnergyPLAN.

technologies expected to play a significant role.

Firstly, the accuracy of the models representing the scenarios has been studied to verify the validity of the hypotheses made; then the electricity demand evolution and the thermoelectric generation, both in terms of annual and hourly values have been analyzed in detail; finally, the function of storages has been further explored to observe the consequences on the overall system.

2.1. Model description

The energy system model presented in this study was developed using EnergyPLAN, a simulation-based tool designed for detailed analysis of national and regional energy systems. EnergyPLAN adopts a deterministic, input–output approach with hourly resolution and is particularly suited for the assessment of smart energy system, enabling the evaluation of cross-sectoral interactions among electricity, heating, cooling, transport, and industrial sectors [45]. The model requires exogenously defined input data, including the annual energy consumption disaggregated by sector and technology, as well as hourly profiles for both energy demands and generation from intermittent renewable energy sources, such as wind, solar, and hydro power. Given the significant reliance of the modelled country on imported electricity, imports and exports are represented through predefined annual values accompanied by hourly distribution profiles. The simulation structure divides energy demand into five key sectors, electricity, heating, cooling, transportation, and industry, each characterized by both an annual aggregate and an associated hourly profile. On the supply side, electricity production is differentiated between centralized power generation – including both electricity-only and combined heat and power (CHP) systems – and iRES. EnergyPLAN also supports the simulation of renewable gas pathways, such as hydrogen and biomethane, thereby enabling sectoral integration and the analysis of energy storage or conversion options [45].

Although the model does not explicitly formulate equations or constraints in the manner of optimization-based tools, its functioning is governed by a comprehensive set of predefined operational rules. These rules include the installed capacities and efficiencies of technologies, priority-based dispatch of generation units, and the technical characteristics of storage and sector-coupling components (e.g., power-to-heat or power-to-gas). The internal balancing mechanism resolves the system hour by hour, dispatching resources according to a fixed priority order that typically favors renewables CHP technologies and storages, with the objective of minimizing fuel consumption and greenhouse gas emissions. More information about the logic behind EnergyPLAN can be found in Refs. [5,45]. Due to its deterministic nature, the model's reliability is highly dependent on the precision and granularity of the input data. Extensive data collection and pre-processing are thus required to produce meaningful results. However, this approach allows for a transparent analysis of cause-effect relationships within the energy system, facilitating scenario comparison and system-level insights into the consequences of various energy strategies and technological pathways [46].

2.2. Scenarios

Four models have been built in EnergyPLAN, the first one being a reconstruction of the 2019 Italian energy system for accuracy estimations and methodology validation through a comparison with the national energy balance; more on this can be found in Section 3.1 and in the Supplementary Material (Section S1). The other three scenarios (FF55, GA40 and DE40) have been reproduced coherently with the descriptions given in the "*Documento di Descrizione degli Scenari 2022*"; Fig. 2 shows a summary of the considered scenarios. However, since not all the assumptions made by the authors are reported in that document, some differences are to be expected.

2.3. Energy demand

Fig. 3a shows the assumed evolution of the energy consumption for each scenario, while Fig. 3b represents the evolution of the electricity generation mix in all the analyzed scenarios. It is worth noting that thermoelectric generation aggregates all fossil fuel-based electricity from both electricity-only producers and CHP plants. The reduction in fossil fuel consumption by 2030 and 2040 (Fig. 3a) results from predefined emission targets, largely influenced by the transport and residential sectors. The scenarios pursue two strategies: electrification and fossil fuel substitution. Electrification improves efficiency, reducing final consumption but increasing electricity demand. Meanwhile, adopting green energy carriers like biomethane and hydrogen aids decarbonization, especially in sectors less suited for electrification. In transport, biofuels support short-term decarbonization but will decline as biomethane production grows. The DDS22 reports that biomethane is expected to be produced locally, while hydrogen mostly imported. To make electrification sustainable, electricity mix is projected to shift towards renewables, mostly PV and wind energy (pink and green bars in Fig. 3b), while the hydro and geothermal capacities are expected to remain the same [3,47]. An increase in electricity net import is anticipated too.

2.3.1. Building sector

The civil sector (residential, commercial, and services) accounted for 40% of Italy's final energy consumption in 2019, over half from fossil fuels. Most energy is used for winter heating in northern regions, with water heating comprising 10%. [48]. It is also the largest electricity consumer, driven by domestic and service sector use. Achieving full decarbonization by 2050 requires major efficiency improvements and demand reductions, estimated based on national plans and building stock energy classes [49,50].

The estimation of the final gas consumption for the civil sector is reported in the DDS22 [3], as well as the predicted consumption of biomethane and hydrogen. Oil and biomass consumption are not present in the DDS22, and their estimation is based on the TYNDP22 addendum for Italy [2] and adjusted by the final fuel consumption reported in the DDS22. These parameters may not be completely accurate, but they enable the analysis of the future of the civil sector. The efficiency of boilers has been taken coherently with some other similar works [29].

In 2019, roughly two million units of heat pumps were accounted for, and electricity consumption has been 18.2 TWh. The average estimated COP is equal to 2.6 [51]. It can also be observed that almost all the heat pumps consumption is related to the service sector. As previously mentioned, the market share of heat pumps is set to increase rapidly thanks to buildings renovation and so is the electricity consumption for heating purposes. It is also worth noting that both air-source and ground source heat pumps are considered, although they have been aggregated.

A portion of the heat demand is supplied by the CHP units through urban district heating networks. In 2019, only a small portion of the demand has been delivered through district heating and its evolution is considered as in Refs. [47,48,51]. The heating devices and their efficiency are reported in the Supplementary Material (Section S1).

Some estimations for space cooling electricity consumption in Italy can be found, but only for 2018 [52] and 2021 [53]; from these the 2019 has been estimated using the average summer temperatures. The COP of air conditioning (AC) systems is evaluated as a seasonal energy efficiency ratio, which is the energy efficiency ratio adjusted for the overall performance of the equipment for the weather over a typical cooling season and the value can be found in Ref. [53] and is equal to 3.2. Cooling demand has risen due to an aging population and AC's role in summer comfort. However, estimating it is challenging as it depends on individual behavior and building renovations. The increase has been estimated as in Ref. [54].

In the GA scenario, a significant amount of heat is expected to be produced using hydrogen, but its role for heating is debated because it is

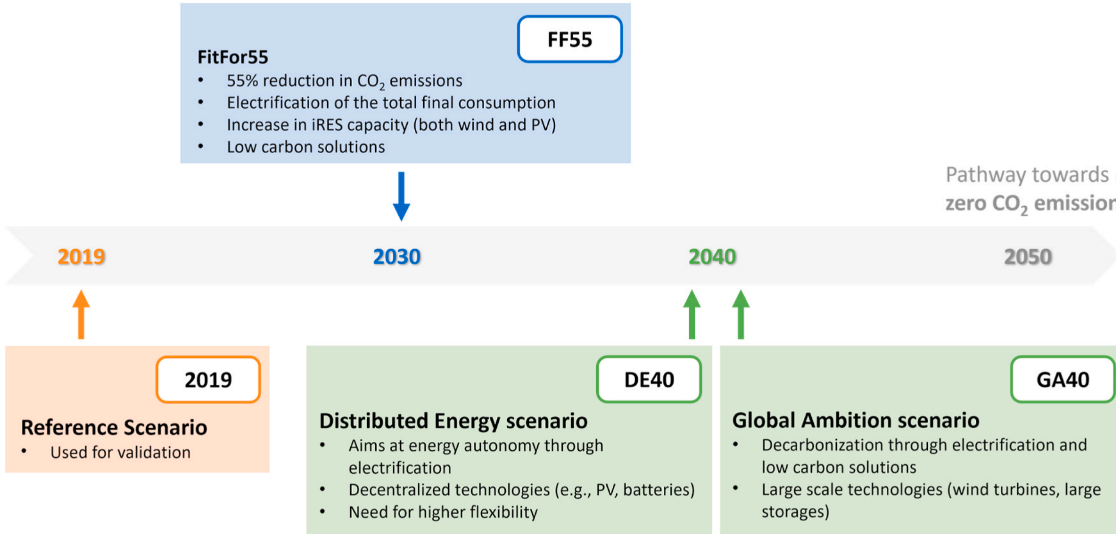

Fig. 2. Scenarios description.

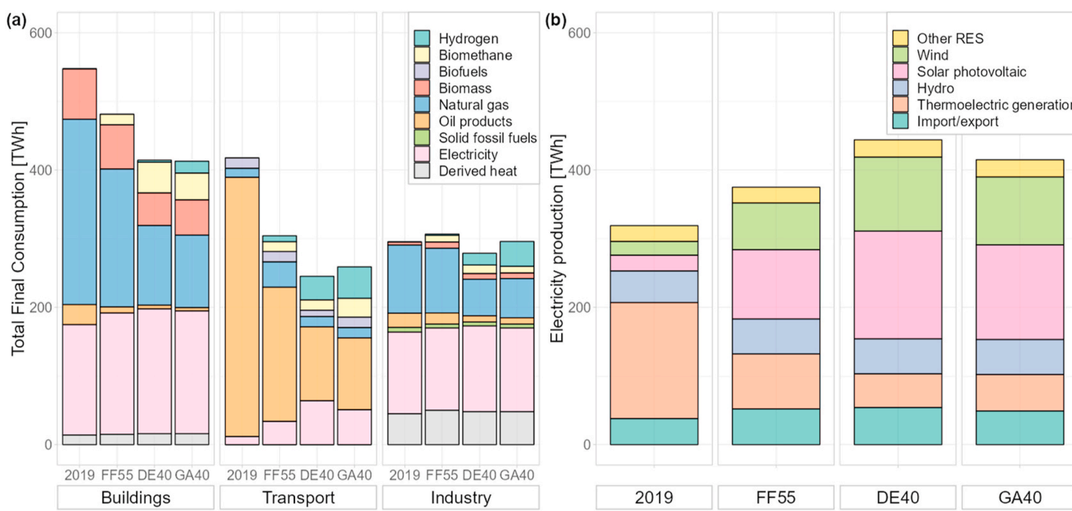

Fig. 3. *(a) Evolution of the energy demand (sector, source and scenario) (b) Electricity production (source and scenario)* [3]. Other RES include bioenergy and geothermal power.

a valuable resource that can be better used in other sectors, such as industry and transportation. Anyway, the share covered by hydrogen is small enough to be compensated with other energy vectors without impacting the overall system [55,56].

2.3.2. Transport sector

Italy's transport sector, with over 40 million vehicles, consumes significant energy, primarily from oil products like diesel and gasoline [57]. In 2019, the transport sector has been responsible for one third of the total CO_2 emissions [58], making its decarbonization crucial. This requires replacing older vehicles with low-emission ones, advancing BEV battery technology, and reducing private car use. The transport sector may also benefit from the diffusion of hydrogen vehicles. As a matter of fact, hydrogen can replace oil products in long haul heavy transports vehicles since the energy density of batteries is small [59]: even though EVs are predominant in all the considered scenarios, hydrogen powered vehicles are expected to constitute a relevant share.

The ENTSO report [43] provides the expected range of the projected market share at European level considering the feedback given by the stakeholders:

- 10%–18% EVs in 2030
- 74%–89% EVs in 2050
- ~2% FCEVs in 2030
- 6%–16% FCEVs in 2050
- 10%–20% heavy good EVs
- 24%–32% heavy good FCEVs

However, it is unclear if these shares are applicable to the Italian market which regarding the transport fleet is stale and tightly bound to the second-hand market [60].

Since in the DDS22 only the total fuel consumption is reported, the oil consumption for the transport sector in future scenarios has been computed comparing different sources [3,43,57,61] reporting trends and predictions both at a national and regional level and estimating the yearly average distance travelled. The projected values are reported in the supplementary material. Biofuels consumption is expected to slightly grow; however, this is an ongoing conversation at a European level because of the competition between food and energy crops [57,62].

2.3.3. Industry sector

Industry is an energy intensive sector and the scenarios that support decarbonization must be studied to decrease its impact; as the focus is on the energy system, only energy-related emissions will be considered. Fuel consumption for industry has been declining in the last 20 years for various reasons, and the emissions from this sector are low if compared to the other sectors and activities.

Hydrogen and biomethane are set to play a key role in the decarbonization of this sector, since for some applications direct electrification is hardly feasible. This is apparent in the GA40 scenario, where their consumption is the highest out of the scenarios analyzed.

Electricity is predicted to be almost the same in all the scenarios, while there are no clear forecasts regarding industrial-derived heat consumption.

In EnergyPLAN the fuel consumption of other sectors, such as the agriculture, forestry and fishing sectors, is considered in the industry tab; therefore, the analysis has been merged too. However, in the DDS22 the consumption of these sectors was not included, so the estimations for these values are based on the data addendum for Italy of the TYNDP22.

2.4. Electricity demand

Electrification is one of the most important aspects of the decarbonization of the end user sector and it consists of the development and diffusion of technologies powered by electricity such as EVs, induction hobs and heat pumps. Therefore, electricity demand is expected to increase considerably in the next 30 years and its hourly profile might change [22]. As previously described, the DE scenario is the one relying the most on the electrification of the end-sectors, while the GA scenario leans more towards the utilization of biomethane and hydrogen. Table 2 reports the predicted evolution of electricity consumption for each scenario analyzed in this work.

Electricity consumption in the transport sector increases by about five times, and it is the greatest among the sectors considered in this analysis and the diffusion of EVs is the main.

The civil sector follows as heat pumps replace gas and oil boilers and as AC demand grows: electricity consumption for heat pumps is estimated to almost double in the 2040 scenarios. On the other hand, industry consumption is predicted to remain constant.

As electrolyzers play a fundamental role in the scenarios analyzed, electricity consumption to produce hydrogen must also be considered and is accounted separately. It is also noteworthy that this quantity is higher in the DE scenario because of a higher installed capacity of electrolyzers that allows greater flexibility.

The most important profiles used are reported in Fig. 4(b and c and f); the chosen profiles come either from official sources (e.g. total consumption) or from other similar works and articles. Since the approach used by EnergyPLAN is deterministic, the choice of consumption profiles, even though justified, is still arbitrary: for this reason, the impact of different profiles of EVs charging and electric heat pumps on the quantities of interest has been studied and they are shown in the Supplementary Material (Section S2.2).

2.5. Electricity production

To efficiently decrease CO_2 emissions the electrification process must be supported by an increase in renewable installed capacity. Solar PV and wind turbines are the technologies with the highest potential in this field; however, due to their intermittent nature, ancillary technologies such as energy storage are needed to guarantee stability and adequacy.

In EnergyPLAN, thermoelectric power plants are divided into electricity-only production and CHP production. Electricity-only power plants are modelled through the installed capacity, their efficiency and the fuel distribution and CHP plants through capacity installed and electric and thermal conversion efficiency: the ratio between electric and thermal efficiency is representative of the cogeneration ratio too. Since the tool does not allow the computation of multiple values of efficiency depending on the fuel, only the overall efficiency of the plant type has been determined by calculating an overall efficiency value. While the 2019 data are known, the DDS22 does not report on the expected amount of cogeneration capacity installed and fuel consumption, so these parameters have been estimated through several iterations with the aim of replicating the results reported by Terna in the same document; results show a reasonable increase in the heat to power ratio, moving from the ratio characteristic of main activity producer CHP (0.21 in 2019) to the one of autoproducers (0.50 in 2019), which is in line with the observations in Ref. [68]. The parameters observed in the iterations have been the total generated power, the total fuel consumption for both electricity and heat production and the associated CO_2 emissions. To better fit the results of the simulations with the data reported in the DDS22 the CHP capacity has been reduced iteratively and the electric efficiency has been slightly decreased favoring the thermal one with respect to the 2019 reported data. Another important hypothesis made has been the amount of power from thermoelectric or dammed-hydro power plants needed to maintain the frequency of the electric system. As a matter of fact, it is hypothesized that thermal power plants will not be necessary for adequacy thanks to the evolution of the auxiliary systems and even if they may be needed, annual differences are likely to be small due to the low production regime in those periods of time.

iRES are modelled through their installed capacity and the hourly production profile that is formed by series of capacity factors (see Table 3 for installed capacity and sources of the hourly profiles and Fig. 4a and d for the normalized hourly generation profiles). For the scope of this work, hydro power plants have been considered iRES, even though traditionally dammed hydro and river hydro are analyzed separately; this simplification has been done due to the lack of reliable separated hourly power profiles. Regarding wind and solar power production, some distinctions have been made: for example, it is indispensable to differentiate between offshore and onshore wind turbines, as profiles change significantly. Likewise, solar energy has been differentiated based on the type of installation, traditional or tracking. Since official data for the selected climatic year are not available, third party's profiles [65,67] have been used for renewable generation. The difference between 2019 Terna data and third-party data has been discussed in Section 3.1. In any case, official data for the year 2010 would not be accurate to represent the evolution of the installed capacity due to the different geographical distribution.

Table 2
Electricity consumption in the four analyzed scenarios.

Electricity consumption [TWh]	2019	FF55	DE40	GA40	Source
Electric cooling	20.0	23.0	26.0	26.0	[5]
Heat pumps	18.2	28.5	38.5	36.5	[18]
Transportation	11.5	34.0	64.0	51.0	[63]
Hydrogen production	0.0	9.0	18.0	16.0	–
Other consumption and losses	270.0	286.7	288.6	272.5	–
Total consumption	319.7	366.0	418.0	396.0	[64]

Table 3
RES capacity installed [3] and sources for the hourly profiles.

Capacity [GW]	2019	FF55	DE40	GA40	Source
Fixed PV	20.9	42.7	49.5	47.6	[65]
Tracking PV	–	32.7	63.7	53.4	[66]
Onshore wind	10.7	18.4	23.1	23.1	[67]
Offshore wind	0	8.5	18.5	15.5	[67]
Hydro power	16.0	16.0	16.0	16.0	[64]
Geothermal	0.8	1.0	1.0	1.0	[64]

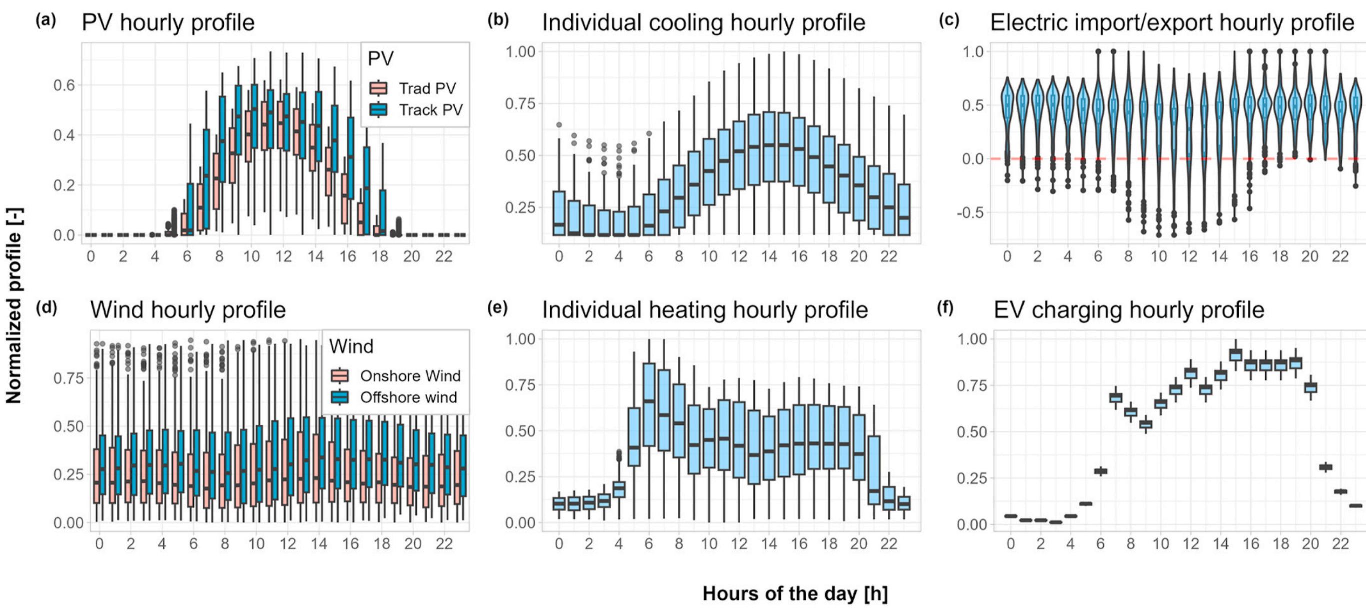

Fig. 4. Hourly profiles for (a) PV generation, (b) Individual cooling hourly profile, (c) Import/export of electricity, (d) Wind generation, (e) Individual heating profile and (f) EV charging profile.

Regarding geothermal energy, current projections [47,69] foresee a limited increase in high-enthalpy geothermal power plants, with installed capacity expected to remain lower than 1 GW by 2030. The primary development pathway for geothermal resources in Italy is expected to involve low-enthalpy applications for heat pump systems in the civil sector, rather than for high-enthalpy large-scale electricity generation. This limitation is mainly due to the geographically constrained availability of suitable geothermal resources, concentrated in specific areas of the country where existing plants are already located. Consequently, the role of geothermal energy in future electricity scenarios remains relatively marginal under current technological and resource assumptions.

Electricity storage systems are modelled through their capacity, maximum charge and discharge power and efficiency. Since *EnergyPLAN* does not support detailed analysis of individual storage technologies, these values have been aggregated. Table 4 presents the total installed storage capacity, including PHES (pumped hydro energy storage). According to recent reports [47,69], the potential for new PHES projects in Italy is largely saturated due to geographical and environmental constraints. However, although PHES facilities are currently underutilized, an increased exploitation of the existing installed capacity is foreseen within the analyzed scenarios, contributing to the system's flexibility needs [47,70]. This increased utilization refers to operational use of the current plants, as no major expansions in installed PHES capacity are planned in the short and medium term [3,47].

Electrolyzers are modelled according to their capacity and efficiency, which are estimated as in Ref. [3] and summarized in the supplementary material (Section S1). Since hydrogen produced locally would not be enough to supply the totality of the demand, both hydrogen import and storage are incorporated into the models.

Italy's dependency on electricity imports is expected to grow in the coming years; thus, accurately modeling this component of the system is crucial for meaningful analyses. However, certain assumptions were necessary: the DDS22 provides annual forecasted import values, while the hourly import profile for future scenario analyses was derived through multiple iterations. These iterations aimed to reduce both overgeneration and thermal power generation, adhering strictly to the international transmission limits specified in Terna's development plan [71]. Fig. 4c reports the profile used in the models of the scenarios considered. However, it is hard to predict what the profile may look like in 2040 as it also depends on the energy politics of the neighboring countries, especially France [72]. Concerning the 2019 model, official data reported by Terna has been used [64].

Particular attention has been paid to the consequences of the integration of large amount of iRES into the system: the analysis has been carried out observing the hourly behavior, through duration and net loads curves, of the main elements of the system that are required to overcome sudden variations in power production, namely thermoelectric power plants and storages.

Table 4
Electric storage capacity installed.

Capacity [GWh]	2019	FF55	DE40	GA40	Source
PHES	56	56	56	56	[3,70]
Utility scale storage	–	71	131	108	[3]
Small scale storage	1	24	44	36	[3]
Total	57	151	231	200	[3]

2.6. Key performance indicators

To enable a clear and quantitative assessment of the evolving role of thermoelectric power plants and electricity storage, a set of relevant KPIs has been introduced. These include:

- Thermoelectric Power Plants Capacity Factor [−]: the ratio between the actual energy produced over a year and the maximum possible energy that could have been produced operating at full installed capacity continuously throughout the year. The calculation of the capacity factor is based on the assumption that the peak power production corresponds to the actual installed capacity, which in practice is generally not the case. Therefore, the values reported are intended to be indicative, primarily reflecting the relative reduction in operating hours rather than providing an exact measure of plant utilization.
- Thermoelectric Peak Power [MW]: represents the maximum instantaneous electric power output delivered by thermoelectric power plants during the year.
- Net Load [MW]: defined as the difference between the total electricity demand and the generation from iRES. It represents the

portion of the demand that must be met by dispatchable sources, such as thermoelectric plants and storage systems.
- Standard Deviation of Net Load [MW]: quantifies the variability of the residual electricity demand after accounting for intermittent renewable energy generation.
- Delta Peak-Valley of Net Load [MW]: defined as the average daily difference between the maximum and minimum net load values.

The last two KPIs, related to net load variability, have been evaluated both with and without the contribution of energy storage systems, in order to highlight the role of storage in mitigating system fluctuations.

These indicators allow for a systematic comparison across scenarios and highlight the operational challenges associated with increased shares of intermittent renewable generation.

3. Results

In this section the main results from the analysis of the proposed scenarios are presented; in particular, in Section 3.1, a thorough assessment of the accuracy of the representation of the energy system and future scenarios is developed. Section 3.2 analyzes the impact of the choice of the hourly profiles over the quantities of interest, while Section 3.3 presents the implications of the increase of electricity demand and renewable generation on thermoelectric generation and Section 3.4 presents the effects of storages on the overall system. Additional details for each section, together with secondary results and complementary analyses, such as seasonal trends, are available in the Supplementary Material.

3.1. Accuracy assessment

The premise of this work is the reproduction of scenarios realized by the Italian TSOs: therefore, the accuracy of the representation of these scenarios on EnergyPLAN has to be studied.

Firstly, the 2019 model of the energy system has been compared to the real one resulting from Terna and ministerial data, both from an annual and hourly point of view. On a yearly basis, differences in fuel consumption are lower than 1% for electricity production and lower than 0.5% in final consumption. In terms of hourly results, the accuracy of the iRES production profiles has been studied and the relative difference between the norms of the official production profiles by Terna [64] and the ones discussed in Section 2.5 [65,67] has been calculated: for solar power production a 2.8% difference was found and 5.0% for wind. Differences are therefore not negligeable, but since the works employed as sources are particularly oriented towards the future, those are acceptable discrepancies. The results of the accuracy analysis are reported in the supplementary material (Section S2.1).

A similar approach was used to assess the accuracy of the future scenarios modelled in EnergyPLAN. As summarized in Section S2.3 of the Supplementary Material, the annual results obtained from the simulations were compared with those provided in the DDS22. The agreement between the values obtained from the models and the reference values is very high in all scenarios, with deviations in total final energy consumption and renewable energy production generally less than 2%. Greater differences can be observed in the estimation of excess generation from renewable energy sources (up to 20%, for the FF55 scenario). However, since excess generation accounts for only a small part of total renewable energy generation (about 2% for the FF55 scenario and less than 5% for the scenarios at GA and DE), even small absolute differences lead to higher relative deviations. With this clarification, the general robustness of the modeling approach can be confirmed.

3.2. Effect of hourly profiles

Since the approach used by EnergyPLAN is deterministic, the hourly profiles affect greatly the final results. Therefore, to understand the actual influence, some studies have been carried out, especially on the energy demand side: different profiles for electricity consumption for

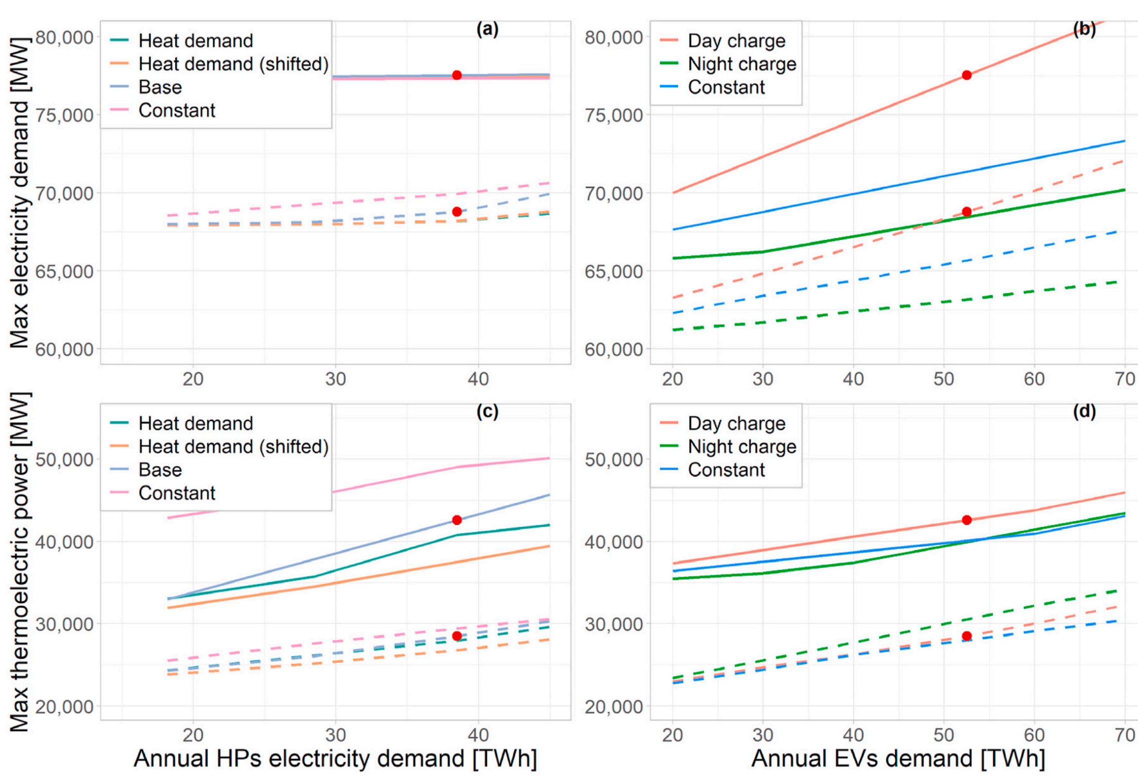

Fig. 5. Maximum (continuous) and 98th percentile (dashed) electricity demand and thermal power as a function of heat pumps and EVs electricity demand and hourly profile, respectively. The red dot represents the base case for the DE40 scenario.

heat pumps and for EVs charging have been considered in the analysis accounting for fairly different strategies that could be employed in the future, such as house pre-heating or vehicles pre-charging. The quantities of interest are the electricity demand and the thermoelectric power plants contributions (Fig. 5) and particularly their maximum hourly values have been studied highlighting the most remarkable differences. The profiles studied are presented in the supplementary material (Section S2.2) and their impacts on the electricity demand and on the thermoelectricity production is shown in Fig. 5.

Fig. 5a and b show the maximum (continuous lines) and the 98th percentile (dashed lines) electricity demand as a function of the annual demand for heat pumps and EVs charge. It can be seen that the peak electricity demand is mostly influenced by the electricity demand for EVs, since Fig. 5b shows a higher increase in the electricity demand as a function of the EVs annual demand (this effect is not depicted in Fig. 5a for heat pumps showing a quite constant trend).

The effect of the increase of the annual demand for heat pumps and EVs charge has been also assessed in terms of maximum thermal power (peak power) for thermoelectric power plants (Fig. 5c and d, respectively). It has been found that the heat pumps demand has a larger impact than EVs one in terms of maximum values. However, differences between the profiles almost disappear when looking at the 98th percentile (dashed lines). Therefore, the chosen electricity profiles impact only on a marginal number of hours. Fig. 5 reports the results only for the DE40 scenario and results for all the scenarios investigated are available in the Supplementary Material (Section S2.2).

3.3. Thermoelectric generation in future scenarios

The duration curves have also been investigated for the four investigated scenarios and is shown in Fig. 6 in terms of electricity demand and thermal power plants peak power.

Fig. 6a reports the duration curve of the electricity demand; as the area below the curve represents the annual demand, the higher the demand, the higher the curve. However, it is interesting to notice that the peak values increase, while the minima remain almost equal in all the scenarios with respect to 2019 levels in red.

The consequences of the higher penetration of the combination of iRES and electricity storage into the system have been also analyzed through the duration curves of the thermal power plants (Fig. 6b). The effect is apparent: on one side the area below the curves, corresponding to the total annual energy produced from thermal power plants, decreases (e.g., the overall share of thermal power plants in the final energy supply decreases). On the other hand, the maximum power produced (peak power) increases (DE40 and GA40) or remains constant (FF55) with respect to today's levels. This does significantly impact the economic performance of the system since peaking units are more expensive and less efficient. The number of hours when thermal power plants production is not required increases depending on the scenario, the highest being the DE40 scenario.

KPIs such as peak thermoelectric generation capacity and capacity factors are employed to assess the evolving role of thermoelectric plants under the analyzed short- and medium-term scenarios. The corresponding results are reported in Table 5. Results confirmed a strong decrease in the capacity factor of thermoelectric plants from the 2019 scenario (0.54) to the 2040 scenarios (0.16 and 0.18 for DE40 and GA40, respectively). This reduction is associated with an increase in the peak power of the thermoelectric plants (from 39,930 MW in 2019 to around 42,600 in DE40 and GA40), which are requested to provide large quantities of power in a reduced number of hours per year to couple with the increase in intermittent renewable energy sources.

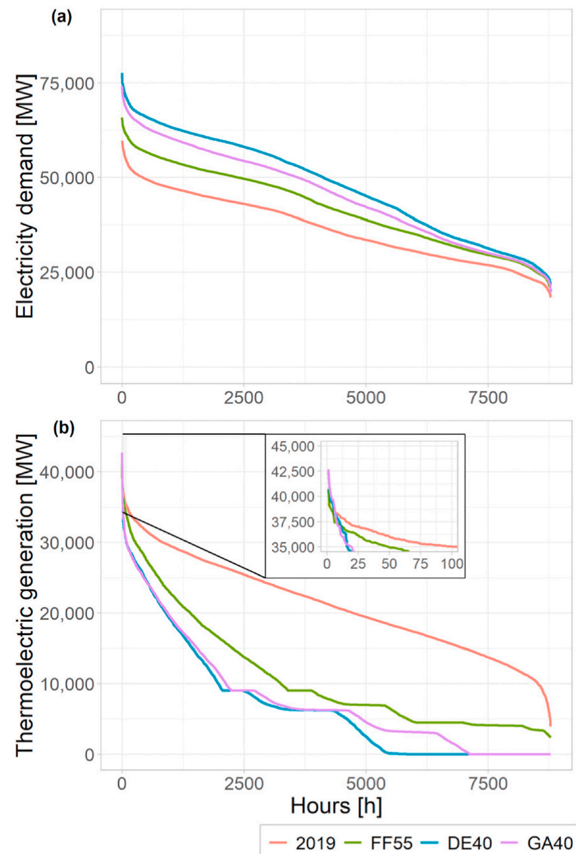

Fig. 6. Duration curves of the electricity demand (a) and thermoelectric generation (b).

Table 5
Thermoelectric power plants KPIs for each scenario.

Scenario	Capacity factor [−]	Thermoelectric peak power [MW]
2019	0.54	39,330
FF55	0.27	40,747
DE40	0.16	42,593
GA40	0.18	42,685

Fig. 7 shows the capacity factors of the various energy generation technologies for the different scenarios and seasons. The figure shows that the higher the generation from renewable energies, the lower the capacity factor of thermoelectric power plants. At the same time, the storage capacity factor is higher when the PV one is higher and wind one is lower, which coincides with the summer period.

The predicted decline in thermoelectric power generation is in line with the results in Ref. [31], which analyzes the carbon intensity of electricity from combined heat and power plants. The study underlines that the carbon intensity of thermoelectric energy in future Italian scenarios is higher than that of the scenario energy mix, even taking into account the possibility of cogeneration, making the use of these plants less environmentally friendly than the national energy mix. The paradigm shift in the use of thermoelectric power plants has also been observed in other studies; for example [37], discusses how the increasing penetration of RES leads to higher operating costs for thermoelectric power plants, due to the greater number of startups required to cope with the higher variability net load.

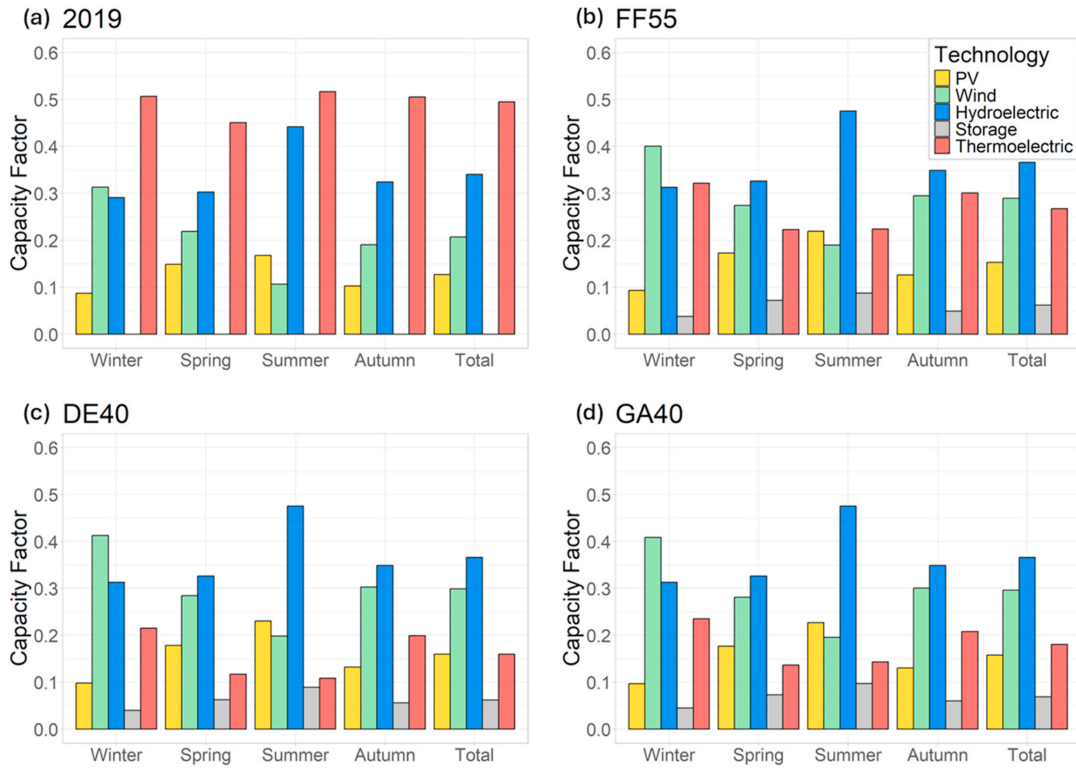

Fig. 7. Seasonal comparison of capacity factors for different scenarios: (a) 2019 (b) FF55, (c) DE40, and (d) GA40.

3.4. *Effect of iRES and electricity storage*

An analysis of the increase in renewable energy capacity installed can be carried out studying the net load, which is defined as the difference between the total electricity demand and the iRES generation: this type of curve is interesting since electricity storages are charged when overgeneration (negative net load) occurs and discharged as soon as possible. This curve highlights the daily interaction between electricity demand, iRES production and the behavior of thermal power plants and storage.

Table 6 compares the relevant KPIs related to the analysis of the net load curves and highlights the effect of electricity storage systems across all scenarios. Among these KPIs, the standard deviation of the net load and the daily peak-valley differences are key metrics for evaluating system variability and the effectiveness of storage in mitigating it. In particular, the peak-valley difference provides insights into the behavior (and ramping requirements) of thermoelectric power plants. Results show that the sample standard deviation of the net load curve increases significantly, as well as the difference between peaks and valleys, moving towards higher iRES penetration. Electricity storage plays a substantial role in mitigating these effects, decreasing standard deviations and average daily ramp rates by approximatively 33% in the FF55 scenario, 40% in the DE40 scenario and 39% in the GA40 scenario. However, even with the contribution of storage systems, all evaluated KPIs remain considerably higher compared to the 2019 reference case, indicating the growing challenges in maintaining system stability under future high-renewable scenarios.

These effects can also be seen in Fig. 8a where peaks and valleys of the net load curve in all the future scenarios immediately stand out: peaks represent hours of low renewable production and high thermal power production and vice versa. Fig. 8b shows how storage helps in shifting and levelling the peaks. However, there may be instances when the storages are empty which can pose serious issues to the stability and reliability of the system during periods of high demand and low renewable production.

The effect of the introduction of the storage on the duration curve of thermal generators is explored in Fig. 9, where the DE40 scenario is taken as reference. In the figure, different storage capacities are investigated, from 100 to 450 GWh (the reference value for the DE40 scenario is 230 GWh). The storage capacity lowers the curve in the mid-section, meaning that the annual generation decreases considerably (−20% with respect to 2019 storage capacity). However, the peak values do not vary at all, which means that the thermal generation required is very high when storages are empty. The asymptotic behavior can be easily seen also by the fact that, after 230 GWh, the curves become closer and closer. This trend aligns with the findings in Ref. [23], which analyzed the diminishing marginal impact of electricity storage capacity on CO_2 emissions. This trend also underlines the fact that, in the analyzed scenarios, the increase in the storage capacity has a limited effect (after a certain threshold) on the peak power of thermoelectric plants, which

Table 6
Net load curve KPIs across all scenarios, with and without the effect of electricity storage.

Scenario	Standard deviation [MW]		Delta peak-valley (mean) [MW]	
	Storage	No storage	Storage	No storage
2019	6875	–	13,011	–
FF55	10,131	13,362	22,724	33,880
DE40	13,371	18,801	30,124	50,337
GA40	12,486	17,191	27,635	45,128

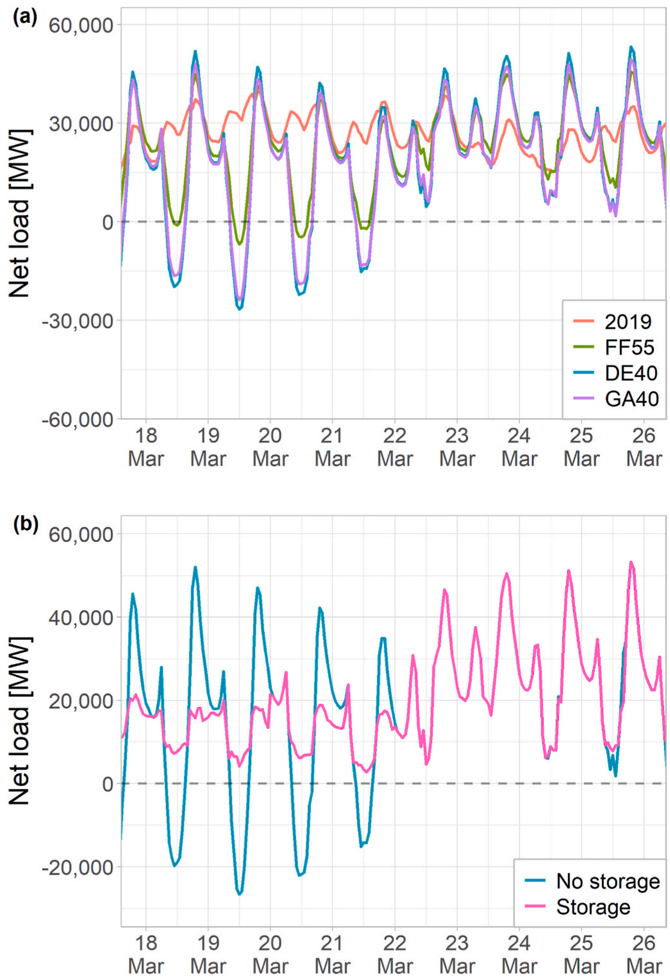

Fig. 8. Net load scenario comparison (a) and storage effect in the DE40 scenario (b).

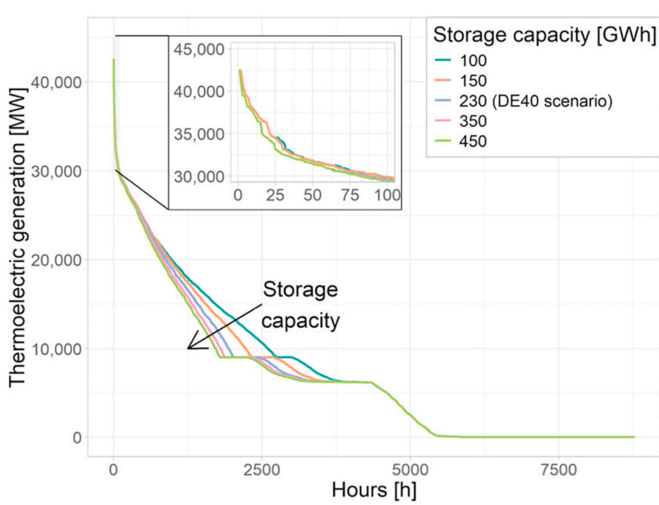

Fig. 9. Duration curve of thermal power plants varying the storage capacity (DE40).

still remains a key element to supply electricity and manage the fluctuations in iRES energy supply (even if for a limited number of hours throughout all the year). The results obtained in the other scenarios are reported in the supplementary material (Section S2.4).

4. Discussion

The results presented in this paper highlight some aspects that are relevant for the ongoing debate on decarbonization policies and strategies at the national level.

The little effect of storage capacity and demand management on the peak demand from thermoelectric power plants calls for the need to modify the organization of the current capacity markets to provide economic support to these technologies. These reforms should provide economic support to such technologies, ensuring compensation not only for the reduced number of operating hours but also for plant availability and startup-related costs [37]. At the same time, considering the demand-side perspective, the current economic value associated with flexibility does not seem to be sufficient to trigger significant shifts in the energy consumption habits of final users. To properly define a price for flexibility, its economic benefits should be better calculated, by considering additional aspects such as the cost savings thanks to avoided expansions on transmission and distribution grids and reserve capacity. With an increasing electrification of both heating and transport sectors, it will be of utmost importance to develop time-of-use tariffs for final users to limit the additional electricity demand during peak hours.

It is important to recognize that the analysis carried out in this study is constrained by the scenarios developed by the Italian TSOs. These scenarios are currently the reference framework for national energy strategies and are based on a series of assumptions discussed and validated at national and international levels. They provide a coherent narrative for the future evolution of the Italian energy system. Nevertheless, they do not integrate more aggressive approaches to sector coupling, flexibility markets, or grid innovation, which are emerging in other countries and could significantly impact system behavior. A future extension of this work will aim to assess the effects of more ambitious flexibility strategies, with a particular focus on the role of demand-side participation.

Additionally, it must be acknowledged that several unpredictable factors could substantially influence the evolution of the energy system. These include potential major economic crises, disruptions in supply chains due to geopolitical events or environmental disasters, and the emergence of disruptive technologies. Technological breakthroughs, such as significant cost reductions in electricity storage or hydrogen solutions, could alter system trajectories considerably. Potential game-changer solutions – such as redox-flow batteries [73], hydrogen-based seasonal storage [40,74], and advanced sector-coupling strategies [75] – could profoundly reshape the flexibility landscape in future decades. However, these technologies still have a low Technology Readiness Level (TRL) and are unlikely to be significant assets for the short- and medium-term scenarios analyzed in this study. Although these aspects lie beyond the scope of the current analysis, they represent crucial areas for future research aimed at enabling fully decarbonized, resilient energy systems.

5. Conclusions

This work provides a detailed hourly analysis of the current and projected Italian energy system for 2030 and 2040, using the 2019 system as a validation reference and baseline.

The study is based on scenarios developed by authoritative national institutions, namely the Italian TSOs, ensuring a robust and credible representation of the country's energy transition pathway. Rather than proposing new decarbonization strategies, the objective of this work is to complement these official scenarios by investigating the short- and medium-term operational challenges associated with increasing shares of intermittent renewable energy sources (iRES) and the corresponding flexibility needs.

The analyzed scenarios were implemented and simulated using the EnergyPLAN model, starting from the published datasets and integrating and reinforcing them with detailed hourly profiles for production and consumption sectors retrieved from additional sources.

The accuracy of the model has been then verified by means of a two-stages approach: first comparing the current energy system (2019) to its reproduction on EnergyPLAN (especially from an hourly point of view), secondly comparing the annual results of the model to the ones reported in the DDS22. Following the validation, an in-depth analysis of the obtained hourly trends was carried out. Special attention was devoted to the impact of increased electricity demand and iRES capacity on the overall system operation, evaluated through specific KPIs such as thermoelectric capacity factors, peak generation, net load variability (standard deviation), and daily peak-valley differences.

The main findings can be summarized as follows:

- To achieve the goals set by the European Climate Law, future scenarios set a great increase in renewable capacity (2.5 times by 2030 and 3.5 times by 2040), building renovation rate (30% by 2030) and electric or hydrogen vehicles share in the transport fleet (respectively 50% and 10% by 2040).
- The energy demand for the end-use sectors is set to change significantly as fossil fuels lose relevance and as electricity, biomethane and hydrogen become the main energy vectors (up to 26% in the 2040 GA scenario).
- Electricity generation is projected to be greatly influenced by the increase of demand because of EVs, heat pumps and intermittent generation, especially considering peak in demand (+25%) and in thermoelectric generation (+8.3%). Partly, this problem can be solved through smart management of the demand and dispatch (−11% in peak demand and −5.8% in peak thermoelectric generation with respect to the profiles used as reference).
- Due to the existence of extended periods of time when renewable production is low and electricity demand is high, thermoelectric power plants are still needed to guarantee the required electricity, even in future scenarios with high penetration of renewables. Despite the number of equivalent working hours is expected to decrease (capacity factor dropping from 0.54 to 0.18), the peak power remains stable at about 40 GW, causing the economic performance to drop quite significantly considering they still need to be always maintained available.
- The progressive increase in net load variability and daily ramping requirements observed in the future scenarios illustrates the operational challenges resulting from a high share of variable renewable generation. Consequently, investments in grid infrastructure will be required to ensure the reliability of the electricity system.
- Electricity storage will play a significant role in providing short-term flexibility to the system storing the excess of electricity for later use and reducing the average daily difference between peak and valleys. However, since there are still times when renewable energy production is low, storage systems are quickly depleted. The storage capacity is strictly connected to the electricity demand and renewable production and their effect on the system shows an asymptotic behavior (results indicate that increasing the storage above about 230 GWh does not influence the thermoelectric power generation).

These results show that a significant evolution of the electricity system is necessary, due to the need of coupling a strong increase in renewable generation with flexibility options. With the assumptions considered in this work, thermoelectric power generation will remain necessary, in addition to other flexibility options (including energy storage and demand side management). This means that also the electricity market mechanisms and regulations will need to be organized for an effective valorization of the flexibility services and a proper allocation of the best solution for each circumstance.

Further works should go deeper into the intricacies of international exchanges of electricity as iRES is projected to greatly increase in most of the European countries and on the role of the combined heat and power generation within systems characterized by abundant electricity from renewable sources, while experiencing scarcity in heat supply. Additionally, further extensions could analyze the impact of variations in economic drivers and technological innovation on the evolution of flexibility needs.

CRediT authorship contribution statement

Andrea Franzoso: Writing – original draft, Visualization, Software, Investigation, Formal analysis, Data curation. **Michel Noussan:** Writing – review & editing, Supervision, Methodology, Investigation, Data curation. **Paolo Marocco:** Writing – review & editing, Supervision, Methodology, Investigation. **Marco Badami:** Supervision, Methodology, Funding acquisition. **Gabriele Fambri:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Marta Gandiglio:** Writing – review & editing, Supervision, Investigation, Formal analysis.

Declaration pertaining to the use of generative AI and AI-assisted technologies in the writing process

The authors only used ChatGPT during the preparation of this paper to improve the English and readability of the text. After using this tool, the authors reviewed and edited the content as necessary, and they take full responsibility for the content of the published article.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.segy.2025.100186.

Data availability

Data will be made available on request.

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