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Modeling the long-term evolution of the Italian power sector: The role of renewable resources and energy storage facilities

Caterina Carà [a,b,c,*], Paolo Marocco [d], Riccardo Novo [a,b,c], Matti Koivisto [e], Massimo Santarelli [d], Giuliana Mattiazzo [a,b,c]

[a] *Dipartimento di Ingegneria Meccanica e Aerospaziale, Politecnico di Torino, Corso Duca Degli Abruzzi 24, Torino, 10129, Italy*
[b] *MOREnergy Lab, Politecnico di Torino, Via Paolo Borsellino 38/16, Torino, 10129, Italy*
[c] *Energy Center Lab, Politecnico di Torino, Via Paolo Borsellino 38/16, Torino, 10129, Italy*
[d] *Dipartimento Energia "Galileo Ferraris", Politecnico di Torino, Corso Duca Degli Abruzzi 24, Torino, 10129, Italy*
[e] *Department of Wind and Energy Systems, Technical University of Denmark, Frederiksborgvej 399, Roskilde, 4000, Denmark*

A R T I C L E I N F O

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A B S T R A C T

The aim of this study is to investigate the long-term planning of the Italian power sector from 2021 to 2050. The key role of photovoltaic and wind technologies in combination with power-to-power systems based on hydrogen and batteries is investigated. An updated version of the OSeMOSYS tool is used, which employs a clustering method for the representation of time-varying input data. First, the potential of variable renewable energy sources (VRES) is assessed. A sensitivity analysis is also performed on the temporal resolution of the model to determine an adequate trade-off between the computation time and the accuracy of the results. Then, a techno-economic optimization scenario is carried out, resulting in a total net present cost of about 233.7 B€. A high penetration of VRES technologies is foreseen by 2050 with a total VRES installed capacity of 272.9 GW (mainly photovoltaic and onshore wind). Batteries are found to be the preferable energy storage solution in the first part of the energy transition, while the hydrogen storage starts to be convenient from about the year 2040. Indeed, the role of hydrogen storage becomes fundamental as the VRES penetration increases thanks to its cost-effective long-term storage capability. By 2050, 74.6 % of electricity generation will be based on VRES, which will also enable a significant reduction in CO_2 emissions of about 87 %.

1. Introduction

Climate change is a worldwide issue which is causing several difficulties and consequences both at human and environmental level. In 2021, the electricity sector emitted more than one third of global energy-related CO_2 emissions [1]. In recent years, energy policies are aimed to limit the global warming, promoting a green transition toward a low-carbon electricity mix and the electrification of energy-intensive sectors, such as transports and heating. In this context, variable renewable energy sources (VRES), characterized by limited environmental impact and high availability, are expanding rapidly, reducing the dependence on conventional energy resources and meeting the rising energy demand [2]. However, their fluctuating behavior causes difficulties in terms of grid stability and mismatch between supply and demand. Electrical energy storage (EES) systems are thus expected to play a key role to cope with the variable and unpredictable nature of VRES [3].

There are different categories of energy storage: mechanical, electrochemical, chemical, electrical and thermal [4]. Batteries are electrochemical devices characterized by high efficiency and fast response time, which makes them an ideal solution for small-size and short-term energy storage applications. Among the different battery types, the lithium-ion technology is characterized by high round-trip efficiency, low self-discharge rate, wide cycling modulation range and long lifetime. It is therefore very suitable for coupling with VRES systems [5].

Electricity can also be stored into chemical energy by producing hydrogen as starting point, which can then act as a multi-purpose energy carrier. In this context, the electrolysis process (by means of electrolyzers) is the most promising route to store electricity in the chemical form of hydrogen [6]. Hydrogen storage is expected to be crucial to achieve high VRES penetration in the electricity mix due to its high energy density and long-term storage capability [7], thereby contributing to the decarbonization process [8]. Compared to traditional

* Corresponding author. Energy Center - Politecnico di Torino, Via Paolo Borsellino 38/16, 10138 Torino (TO), Italy.
E-mail address: caterina.cara@polito.it (C. Carà).

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Nomenclature

$BATT_S$	*Battery energy component*
$BATT_T$	*Battery power component*
BIO-FUELS PP	*Bio-fuel based power plant*
EES	*Electrical energy storage*
ELC DIS	*Electricity distribution*
ELECTRICITY FD	*Electricity final demand*
ELECTRICITY SC	*Electricity secondary commodity*
ELY	*Electrolyzer*
ESM	*Energy system models*
ESOM	*Energy system optimization model*
FC	*Fuel cell*
FOSSIL PP	*Fossil fuel based power plant*
GAS CHP	*Natural gas based cogeneration plant*
GAS EL	*Natural gas based power plant*
GEOTHERMAL	*Geothermal plant*
GHG	*Greenhouse gas*
HT	*Hydrogen tank*
HYDRO PUMPED	*Hydro pumped*
HYDRO RESERVOIR	*Hydro Reservoir plant*
HYDRO RIVER	*Hydro Run of river plant*
HYDRO STORAGE	*Hydro storage*
IMP ELECTRICITY	*Import of electricity*
IMP/EXT BIO-FUELS	*Import and extraction of bio-fuels*
IMP/EXT FOSSIL FUELS	*Import and extraction of fossil fuels*
LP	*Linear programming*
MILP	*Mixed integer linear programming*
OFFSHORE WIND	*Offshore wind plant*
ONSHORE WIND	*Onshore wind plant*
P2G	*Power-to-gas*
P2P	*Power-to-power*
PHOTOVOLTAIC	*Photovoltaic plant*
PNIEC	*National Energy and Climate Plan*
RDs	Representative days
RES	*Renewable energy sources*
SNG	*Synthetic natural gas*
VRES	*Variable renewable energy sources*

long-term energy storage solutions (e.g., pumped hydro storage), hydrogen is characterized by high flexibility in terms of site topology and possibility of decentralized applications [9,10]. Power-to-gas (P2G) systems allow the conversion of the surplus renewable electricity into hydrogen, which can be stored and later used by a fuel cell or other converters such as thermal motors to generate electricity according to a power-to-power (P2P) route [10], or further processed to produce synthetic natural gas (SNG), synthetic liquids and, more in general, synthetic chemicals. Hydrogen can also be employed in both heating and transport sectors [6,11].

In this context, there are several policies at European level proposing challenging decarbonization targets. In 2019, the European Green Deal set a 55 % reduction in greenhouse gas (GHG) emissions by 2030 compared to 1990 [12] and the net-zero emission goal by 2050. In line with the European strategy, Italy has strengthened its decarbonization path to promote economic and social sustainability, also considering environmental safeguard. In 2020 the Italian government published the National Hydrogen Strategy Preliminary Guidelines, which discusses the role of hydrogen in contributing to the decarbonization process, and in 2023 the updated version of the National Energy and Climate Plan, which defines the roadmap for a sustainable energy transition [13].

At European level, long-term scenario analyses have been conducted to assess and estimate the role of hydrogen and its impact on the decarbonization of the energy system. Scheller et al. [14] investigated the role and benefits of hydrogen and hydrogen-based energy carriers in Germany by 2030, also demonstrating their essential contribution in the energy system with a coverage of 24 % of the final energy demand by 2050. Martins et al. [15] explored the potential role of hydrogen in the energy transition of Ireland as an energy vector and storage medium to reduce greenhouse gas emissions. They showed a potential annual reduction of up to 6.1 $Mt_{CO2,eq}$ using hydrogen as renewable energy storage, as grid balancing through the deployment of P2G systems, and as a replacement for fossil natural gas for backup power generation and for the industrial and heating sectors. Brey et al. [16] investigated the use of hydrogen in the Spanish energy system to enable high penetration of VRES technologies by storing excess electricity into chemical energy. Feijoo et al. [17] proposed a long-term energy planning model to explore the decarbonization of the Croatian energy system, taking into account the links between the electricity, heat, transport, industry and electro-fuels (e.g. hydrogen) sectors. They pointed out the main role of power-to-X technologies to increase the flexibility of the system and avoid overproduction of energy.

The Italian energy system has also been studied in the literature by means of projections of GHG emission reductions through VRES penetration in the electricity sector, including the electrification of transport and heating sectors. Colbertaldo et al. [18] modeled an integrated power and transport system analyzing the role of P2G and hydrogen. They demonstrated that it is possible to achieve a 57 % share of VRES in the electricity mix by 2050, although no European GHG emission reduction target was met in the proposed scenarios. In a further investigation of the Italian case study [19], they also analyzed carbon-neutral scenarios up to 2050, highlighting the need for a massive CO_2 emissions reduction in several sectors, an increase in electricity generation from renewables to 20 times today's capacity, the use of storage systems (considering also the hydrogen energy vector to enable sectors coupling), the use of biogenic sources and CO_2 capture. Jafari et al. [20] developed a capacity expansion optimization model to investigate the interaction between energy storage facilities and VRES. In particular, EES systems were found to play a key role in enhancing the renewable energy sources (RES) penetration. A high RES penetration was observed even in the absence of CO_2 constraints. Bellocchi et al. [21] investigated the electrification of both the transport and heating sectors in Italy. Their assessment indicated a reduction in CO_2 emissions by 70–75 % compared to the 2017 levels and a RES share of 65 % in the electricity production. In addition, in another study applied to Italy [22], the same authors explored the crucial role of hydrogen and showed how the full utilisation of renewable energy sources in electricity generation, the electrification of private transport, and the use of green hydrogen and electric fuels can result in a CO_2 emissions reduction of up to 49 %. Bompard et al. [23] proposed an electricity triangle for the energy transition, comprising electricity generation from VRES, the use of electricity as an energy vector and the electrification of final energy uses. This approach is projected to achieve an 85.6 % RES penetration in electricity supply by 2050, accompanied by a CO_2 reduction of 68 % compared to the 2020 emissions level. Lombardi et al. [24] investigated the decarbonization of the Italian power sector, applying a non-traditional approach that offers detailed options for the transformation of the electricity system. In particular, they showed that achieving its decarbonization by 2050 requires solely photovoltaic and storage systems, emphasizing their necessity and significance.

Although long-term energy system models are the main tool for conducting future analysis and forecasts, both the time representation and the description of VRES remain a weakness. Ringkjøb et al. [25] showed how a coarse time-step in energy system models can lead to un-favorable investments, overestimation of VRES and underestimation of costs. In fact, energy system models (ESMs) use sample periods to limit the computational burden of the simulation [26]. Generally, a rigid time series representation is implemented, where each year is divided into time slices identified by a season, a day type (i.e., season day) and a daily time bracket (i.e., day fraction) [27]. Nevertheless, this time framework can lead to inaccurate sizing of VRES and storage technologies [28], and becomes more evident the higher the relevance of time series, such as in case of a high VRES share [29]. Novo et al. [30] proposed a time series clustering approach that seeks to overcome this problem and showed higher accuracy in modeling energy storage facilities and VRES variability. Specifically, they applied a clustering method to time series input data to identify a set of representative time periods: all the days of a given year were clustered into a given number of representative days (RDs) so that the group members were as similar as possible. They found that there is a minimum number of RDs that allows to obtain a good compromise between accuracy of the results and complexity of the problem.

One of the gaps in recent scientific works is the lack of comprehensive long-term energy systems planning, in which a techno-economic optimization is carried out, taking into account an adequate temporal representation and description of the VRES. The aim of this work is to elaborate a model of the Italian power sector, performing a long-term planning from 2021 to 2050, using an updated version of OSeMOSYS where time series clustering is applied [30]. The model also includes a potential assessment of the photovoltaic and onshore wind technologies, in order to estimate the actual expandability of these solutions. Both batteries and hydrogen are introduced as electrical energy storage systems. The role of VRES and storage facilities (batteries and hy-drogen) in promoting a progressive decarbonization of the Italian power sector is then explored from an economic and environmental perspective.

The structure of this work is the following: Section 2 presents the methodology for the energy system modeling; main techno-economic assumptions are also shown, along with the scenarios that will be investigated; in Section 3 results are presented and discussed; and finally the main conclusions are summarized in Section 4.

2. Methodology

This section illustrates the overall methodology implemented to examine the future structure of the Italian power system, where VRES and storage facilities are expected to play an important role. First, Section 2.1 explains the modeling framework used; Section 2.2 introduces the actual structure of the Italian power sector; Section 2.3 describes the energy model scheme adopted and illustrates the input data of the model; finally, Section 2.4 describes the main analyses performed in this work.

2.1. Modeling framework

In the context of decarbonizing energy systems, the investigation of the current energy situation and future projections is often addressed through the development of ESMs, which can be divided into two main categories, namely top-down and bottom-up models [25,31].

More specifically, energy system optimization models (ESOMs), which are an important branch of bottom-up energy models, provide an integrated, technology-rich representation of the whole energy system for long-term, multi-period time horizon analysis [32]. Therefore, they represent an important tool to offer insights related to energy, environmental and climate policy strategies, proposing the best set of technologies to achieve specific targets at minimized costs under specific constraints [33]. Some of the most widespread tools are MESSAGE [34] and TIMES [35] modeling framework, and the open-source Balmorel [36], TEMOA [37], Calliope [38] and OSeMOSYS [39].

For this case study, the energy model has been built using OSeMOSYS (Open Source Energy Modeling System), which is a deterministic, LP/MILP-based, open source, multi-year modeling framework [39]. The physical model structure is built on the following sets: *regions*, *fuels*, *technologies* and *storages*. In OSeMOSYS, the objective function (OF) is the minimization of the net present cost (NPC) of the energy system, given by the sum of the discounted costs (including capital, fixed and variable terms) of *technologies* and *storages* over *regions* and *years*.

This work implements an updated version of OSeMOSYS, where a time series clustering approach is proposed to achieve high accuracy in VRES and storage sizing at limited computational cost [30]. The aim of the time series clustering is to group all the days of the year into a predefined number of groups (i.e., representative days) so that the group members are as similar to each other as possible. The clustering process, which is based on the k-means algorithm, is performed by minimizing a distance measure of the attributes between each group member [40]. The attributes considered in the aggregation process are the profiles over the year of solar, onshore and offshore wind capacity factor and electricity demand.

2.2. The Italian context

At present, the Italian electricity supply strongly relies on fossil power plants, which exploit resources such as coal, oil, natural gas and non renewable industrial and municipal waste [41]. In 2021, the total electricity production was equal to 289.1 TWh, with a thermoelectric share of 65.6 % (consisting in both fossil fuel and bio-fuel based power plant) and a renewable share of 34.3 %. Fig. 1 (a) shows the monthly variation in the electricity demand during the year 2021; it can be seen that it reached a peak during the summer season, from June to August. Fig. 1 (b) shows the production share of the different technologies exploited in 2021: the main renewable technologies used were hydro-power (16.4 %), photovoltaic (8.7 %), onshore wind (7.2 %) and geothermic (2.0 %) systems. A transition toward a lower carbon electricity mix is necessary to achieve future targets in terms of GHG emission reduction and higher sustainability.

2.3. Energy model

2.3.1. Reference energy system

A simplified reference energy system of the Italian power sector (including *fuels*, *technologies* and *storages*) is shown in Fig. 2. A country-level representation is considered, with a single-node approach. The different fossil fuels commodities and technologies are summarized respectively into a unique vertical line (FOSSIL FUELS) and boxes (IMP/EXT FOSSIL FUELS, FOSSIL PP). However, the Italian power system relies on import/extraction, electricity-only power plants and combined heat and power plants, for a total of 15 *technologies*, exploiting coal, oil, natural gas, non renewable industrial and municipal waste. Analogously, for the sake of clarity, in Fig. 2 biofuels and their associated technologies are represented respectively into a unique vertical line (BIO-FUELS) and boxes (IMP/EXT BIO-FUELS, BIO-FUELS PP). However, biofuels-based power plants are diversified into import/extraction, electricity-only and combined heat and power plants, for a total of 14 *technologies*, exploiting liquid biofuels, primary solid biofuels, renewable municipal waste and biogas. The electricity vectors refer to the secondary commodity (ELECTRICITY SC) and final demand (ELECTRICITY FD). Finally, the following renewable energy sources technologies are considered: onshore wind (ONSHORE WIND), offshore wind (OFFSHORE WIND), photovoltaic (PHOTOVOLTAIC), geothermal (GEOTHERMAL), hydro run-of-river (HYDRO RIVER), hydro reservoir (HYDRO RESERVOIR). A more detailed scheme is included in the Supplementary Material.

As shown in Fig. 2, in OSeMOSYS, storage systems are modeled by means of *storages*, to which *technologies* are associated allowing the process of charging and discharging. Three different *storages* are considered: the battery storage ($BATT_S$), the hydrogen tank (HT) and the hydro-pumped storage ($PUMPED\ HYDRO_S$). The electrolyzer (ELY) and the fuel cell (FC) are the *technologies* required to charge and discharge the hydrogen tank, respectively. ($BATT_T$) is the *technology* included in

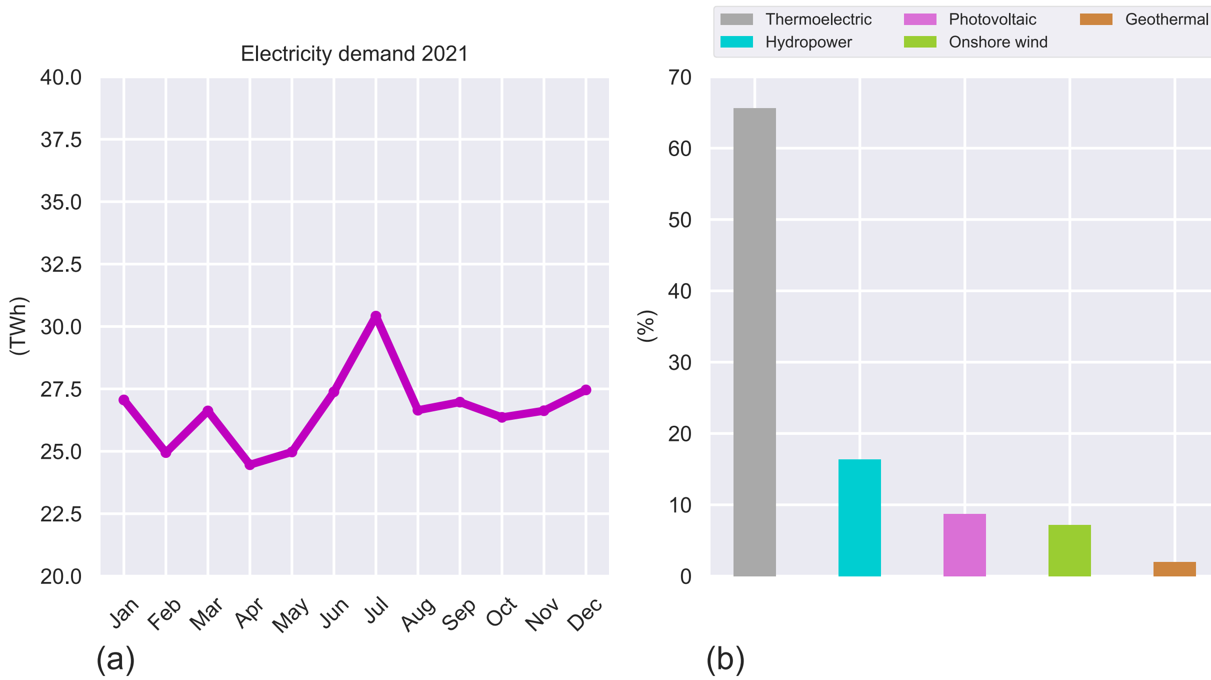


Fig. 1. (a) Monthly electricity demand in 2021 [41]; (b) Electricity production share by technologies in 2021 [41].

OSeMOSYS to allow the charging and discharging of $BATT_S$, and finally PUMPED $HYDRO_T$ is the *technology* associated with PUMPED $HYDRO_S$.

2.3.2. Input data

This section first describes the VRES potential assessment. Then, the different assumptions about the electricity demand variation, the VRES representation and the techno-economic parameters of the different technologies are shown.

2.3.2.1. Renewable potential assessment. Potential assessment is a keypoint in the study of energy systems with high renewable penetration to reliably define the actual availability of the involved renewable energy sources. From the literature, the best and most reliable approach to estimate the potential at national level has not yet been identified. In particular, five different potential categories can be considered when assessing the potential of renewable energy sources [42]: theoretical, geographical, technical, economic and feasible.

For this case study, the implemented method relies on the Geographical Information System (GIS), which allows the use of geospatial information by means of raster layers and vector maps. The technical potential of onshore wind and photovoltaic technologies is determined.

Subsequently, the results obtained are updated by comparing them with further methodologies, in order to improve the reliability of the results. Lastly, the assessment of offshore wind potential takes into account the recent projects of the Italian Wind Energy Association (ANEV).

2.3.2.2. Onshore wind and photovoltaic potential assessment. The estimation of the availability of onshore wind and photovoltaic technologies is performed applying different exclusion criteria, which are divided into physical and technical constraints, built environment exclusion criteria and constraints related to legislation, environmental limitation for flora and fauna safeguard. All these constraints are implemented using their geographical layers (*shapefile format* or *vector map*), which are subsequently easily manipulated using QGIS tool.

For the onshore wind technology, the first geographical layer considered is the average wind speed available at 150 *m* altitude, which is a typical wind turbine hub height and also suitable for future new installations [43]. The wind speed values refer to the wind turbine classes of the International Electrotechnical Commission (IEC 61400-1) [44], as shown in Table 1. The identification of the theoretically useable areas is done by considering areas with an average wind speed equal or higher than 6 m/s.

Regarding the photovoltaic technology, the first constraint considered is the solar energy source in terms of Global Tilted Irradiation (GTI), which is the average daily sum of the global tilted irradiation for PV modules fix-mounted at optimum angle. The minimum acceptable value is set at 1200 kWh/m^2, which is the inverter activation value [45].

Starting from wind speed and global tilted irradiation *shape-files*, the constraints reported in Table 2 are applied subtracting exclusion areas, by means of layers *"Difference"*, or applying a buffer distance around specific elements, using the *"Buffer"* function. Fig. 3 shows the overall procedure scheme.

After computing the actual available area for the onshore wind and photovoltaic technologies, specific power plants densities equal to 7 MW/km^2 (wind) and 82 MW/km^2 (photovoltaic) are considered for the potential assessment [46]. It is supposed that all the available area is completely covered by onshore wind and photovoltaic power plants. Table 3 (first column) reports the output results, which can be classified as technical potentials.

The obtained technical potentials are computed considering the various environmental limitations, economic aspects and also safety constraints. Nevertheless, also social factors can influence the planning decisions [47]. Harper et al. [48] developed a multi-level approach to estimate the UK onshore wind potential also considering both social and political aspects, such as people qualification level, mean age, political orientation, from a statistical analysis. They showed that, in the UK case study, the techno-economic potential of 220 GW decreased to a feasible potential of 13 GW and 4 GW when applying *soft* and *extreme* criteria, respectively. For this Italian case study, due to lack of information for both social and political statistical parameters, it is assumed the same percentage decrease of the UK case study to move from the technical to the feasible potential. Final results are shown in Table 3 for both the *extreme* and *soft* criteria.

2.3.2.3. Offshore wind potential assessment. Nowadays, offshore wind

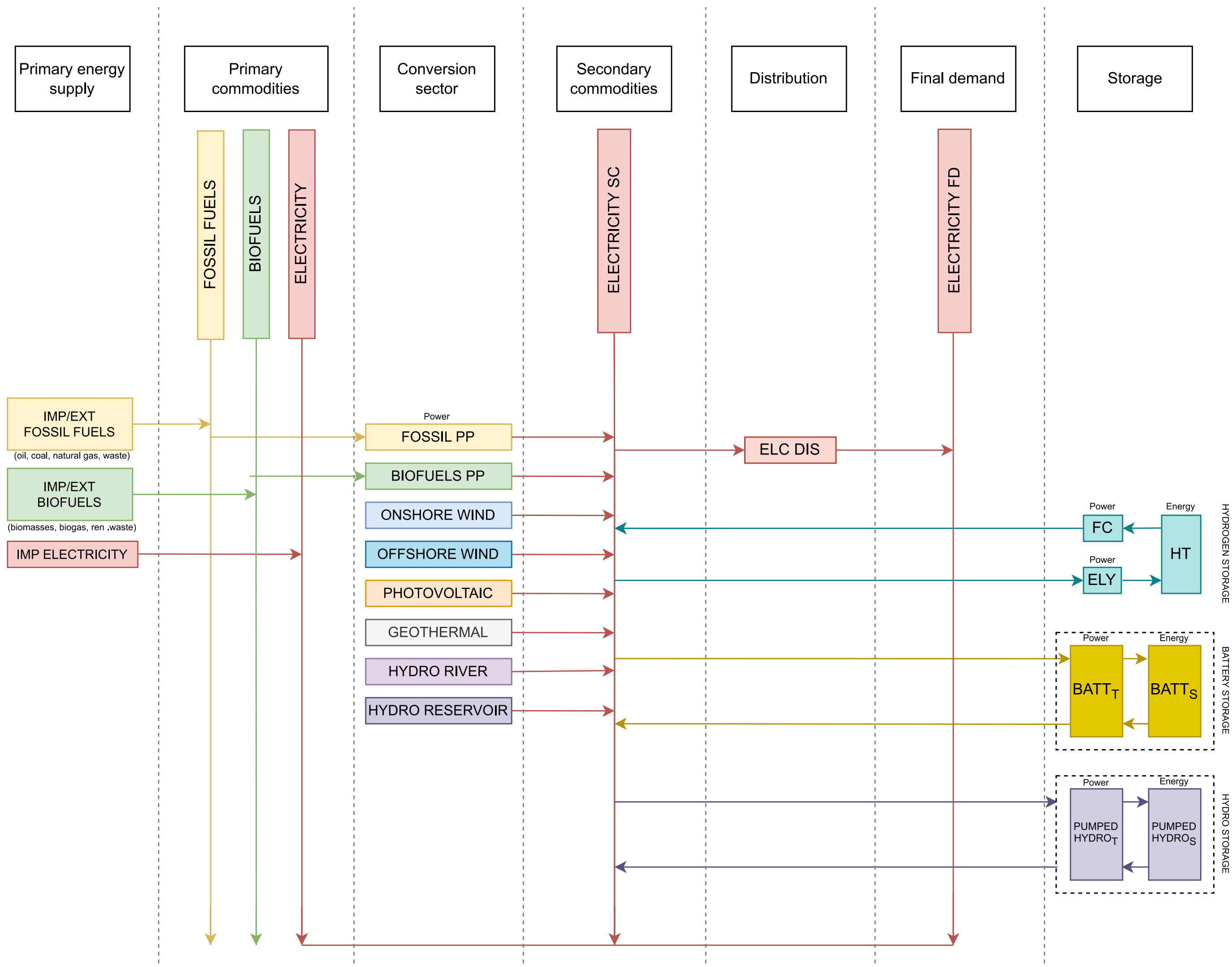


Fig. 2. Simplified reference energy system of the Italian power sector. A more detailed scheme is included in the Supplementary Material.

Table 1
IEC 61400-1 wind turbine classes [44].

	Wind turbine class			
	I	II	III	IV
Annual average wind speed (m/s)	10	8.5	7.5	6

Table 2
Environmental, economic and safety constraints for potential assessment.

Parameter	Value	Ref.
Natura 2000 Network	–	
Important Bird Areas	–	
Water bodies	>200 *m*	[50–52]
Elevation (altitude)	<1500 *m*	[53,54]
High voltage transmission network	>200 *m* and <10 km	[55]
Railways, roads and highways	>200 *m*	[56,57]
Airports	>3 km	[58–60]
Urban Areas	>200 *m*	[61]
Terrain slope onshore wind	<30 %	[62]
Terrain slope PV	<20 %	[54]

power plants are scarcely installed in Italy, with a bottom-fixed offshore wind farm of 30 MW near Taranto harbor. Nevertheless, several efforts are being made to develop and exploit also the offshore wind source. According to estimates by the Italian Wind Energy Association (ANEV) [49], offshore wind potential will amount to 5.5 GW by 2030. Furthermore, thanks to the enhancement of the national electricity transmission grid by TERNA, the future and feasible installable capacity is estimated to reach 95 GW.

For this case study, a maximum potential for the offshore wind technology of 5.5 GW by 2030 and 95 GW by 2050 is assumed.

2.3.2.4. Electricity demand. The annual electricity demand in Italy was about 319.9 TWh in 2021, with a higher load in the summer season, as shown in Fig. 1. An increase in the electricity demand is assumed from 2021 to 2030 based on the Italian National Trends [63]. In particular, the values for electricity demand are taken from the NECP 2019 [64], which takes into account final electricity consumption in the various sectors. A massive electrification of the residential, lighting, heating and industrial sectors is planned by 2030. The transport sector is also to be converted by 2040. For this case study a linear increase is supposed from 2021 to 2025, from 2025 to 2030, and from 2030 to 2040. Finally, from 2040 to 2050 the same growth rate of the previous decade is assumed. Fig. 4(a) shows the evolution of the electricity demand over the model time period. Considering the timeseries of the electricity demand, the

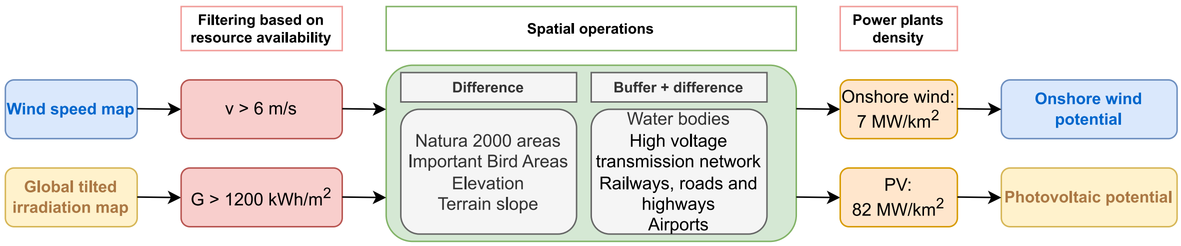


Fig. 3. Onshore wind and photovoltaic potential assessment procedure.

Table 3
Onshore wind and photovoltaic technical potential in Italy.

	Technical potential	Extreme criteria	Soft criteria
	TW	GW	GW
Onshore wind	1.46	86.2	411.2
Photovoltaic	6.70	26.5	126.5

year 2019 is taken as a reference for the electricity profile variation [41]. Indeed, the year 2020 has a lower demand profile due to the Covid-19 shutdowns and the year 2021 still faces some long-term effects determined by the lockdown [65].

2.3.2.5. Time series aggregation. The importance of representing time-varying input data in energy system models is closely related to the temporal variation of renewable production and energy demand. As previously explained, while the traditional approaches use average parameters for time-varying data, the clustering method (k-means) is used to define the representative days based on specific attributes [30]. Furthermore, each day consists of a specific number of time intervals (*daily time brackes*), which is assumed to be equal to 5 for this case study [27,66]. The total number of time slices is defined as the number of RDs multiplied by the number of time intervals.

2.3.2.6. Capacity factor of variable renewable energy sources. The annual profiles of VRES capacity factors (CF) are used to take into account the variation in VRES production over the year [67]. Fig. 4(b) shows the solar, onshore and offshore wind capacity factors during the course of the year 2019. Solar CF reaches higher values during the summer season, from June to August, and sharply decreases during winter season. Onshore and offshore wind technologies behave in the opposite way, reaching higher values in winter with a peak in the month of February and December, respectively. Although the CF evolution over the year is similar, offshore wind CF is always higher compared to onshore wind CF.

As a conservative hypothesis [68], no improvements in the CF time series are assumed through-out the years of the model period.

2.3.2.7. Techno-economic and environmental assumptions. Table 4 shows the main techno-economic assumptions for the estimation of the CAPEX and replacement costs of the renewable technologies and storage facilities of the Italian power system. Capital cost projections are implemented to represent future costs evolution. Specifically, the CAPEX of fossil fuel-based and biomass-based power plants, hydro power plants and geothermal power plants are expected to either remain constant or undergo a limited cost decrease, given their high maturity level. In contrast, VRES technologies (such as photovoltaic, onshore and offshore wind systems) are still in the development phase and are therefore expected to experience a strong cost reduction [69]. Battery storage systems will also experience a significant reduction in cost, due to the growing interest and their potential role when integrated with VRES power plants. In this analysis, the battery cost (the Li-ion typology is considered) is divided into power- and energy-related contributions applying a bottom-up cost model [70], analogously to what proposed by Cole et al. [71]. A reduction in the cost of PEM electrolyzers and PEM fuel cells is also expected due to mass production and research

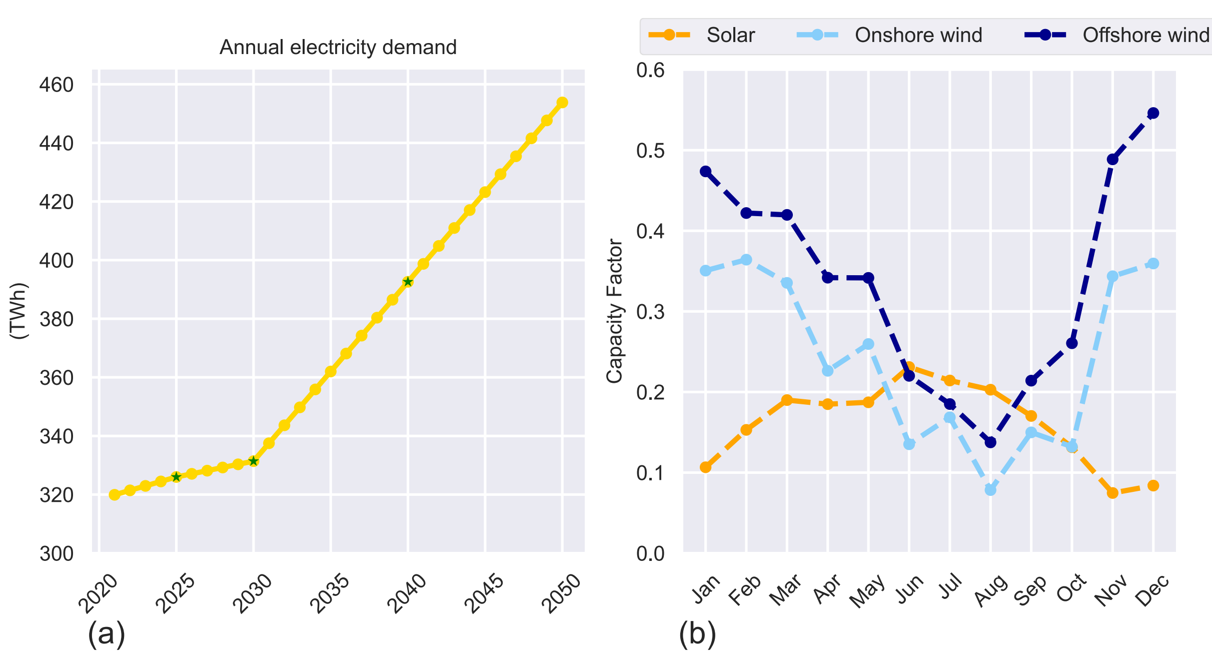


Fig. 4. (a) Electricity demand projection [63]; (b) Solar, onshore wind and offshore wind capacity factor variation over the year 2019.

Table 4
Techno-economic assumption (CAPEX and replacement) of power components and storages facilities [69,76,77].

	Capital cost (€/kW)				Operational life
	2020	2030	2040	2050	
PHOTOVOLTAIC	560	380	320	290	25 y
ONSHORE WIND	1120	1040	980	960	25 y
OFFSHORE WIND	2120	1800	1680	1640	25 y
HYDRO RESERVOIR	3000	3000	3000	3000	55 y
HYDRO RIVER	2440	2440	2440	2440	55 y
PUMPED $HYDRO_T$	3500	3500	3500	3500	55 y
GEOTHERMAL	4970	4970	4970	4970	30 y
$BATT_T$	228	97	77	57	10 y
ELY	1188	701	382	314	20 y*
FC	1520	800	650	500	20 y*
	Capital cost (€/kWh)				Operational life
	2020	2030	2040	2050	
$BATT_S$	241	105	79	55	10 y
HT	15	15	15	15	20 y

*stack lifetime of 10 years.

development [72,73]. The cost of the electrolyzer and fuel cell stacks is assumed to be a fraction of the total CAPEX, equal to 40 % and 50 % for electrolyzer and fuel cell technologies, respectively [74]. Concerning hydrogen tanks, it is supposed no cost evolution over the selected time period, due to the high maturity level of the steel pressure vessel technology [75]. Operational life values are also shown in Table 4 to estimate when the replacement occurs. Tables 5–7 show fixed and variable operational costs.

As previously mentioned, PEM electrolyzers are selected as technology for the hydrogen production, due to their excellent dynamic behavior and thus high compatibility with VRES [78]. PEM electrolyzers efficiency is assumed equal to 65 % [79,80], while 51 % efficiency is considered for PEM fuel cells [81]. Concerning the battery technology, lithium-ion batteries are chosen for this analysis, due to their specific features, such as high round-trip efficiency, low self-discharge rate, wide cycling modulation range and long lifetime [82]. Charging and discharging efficiency of Li-ions batteries is set to 90 % and their energy-to-power ratio is constrained in the range from 0.5 to 2. Hydrogen tanks are assumed as a pressurized vessel.

In addition, emission factors for fossil fuel-based technologies per unit of activity are collected to also perform an environmental analysis and estimate the CO_2 emissions of the Italian electricity sector over the years. They are directly related to the primary energy content of the respective fuel (coal, oil and natural gas). A constant value for the emission factor of the imported electricity is conservatively hypothesized from 2021 to 2050. The assumed values are summarized in Table 8.

Table 5
Techno-economic assumption (fixed OPEX) of power components [69,76,77].

	Fixed cost (€/kW)			
	2020	2030	2040	2050
PHOTOVOLTAIC	11.30	9.50	8.10	7.40
ONSHORE WIND	14.00	12.60	11.59	11.34
OFFSHORE WIND	50.00	39.00	34.00	33.00
HYDRO RESERVOIR	25.50	25.50	25.50	25.50
HYDRO RIVER	8.20	8.20	8.20	8.20
PUMPED $HYDRO_T$	30.00	30.00	30.00	30.00
GEOTHERMAL	95.00	95.00	92.00	92.00
$BATT_T$	5.70	2.41	1.93	1.43
ELY	47.52	21.03	9.47	6.28
FC	60.80	32.00	26.00	20.00

Table 6
Techno-economic assumption (variable OPEX) of power components [69,76,77].

	Variable cost (k€/GWh)			
	2020	2030	2040	2050
PHOTOVOLTAIC	0	0	0	0
ONSHORE WIND	1.50	1.35	1.24	1.22
OFFSHORE WIND	5.00	3.89	3.42	3.25
HYDRO RESERVOIR	0	0	0	0
HYDRO RIVER	0	0	0	0
PUMPED $HYDRO_T$	0	0	0	0
GEOTHERMAL	0.32	0.32	0.32	0.32
$BATT_T$	0	0	0	0
ELY	0	0	0	0
FC	0	0	0	0

Table 7
Techno-economic assumption (variable OPEX) of fuels [69,76,77].

	Variable cost (k€/GWh)			
	2020	2030	2040	2050
IMP ELECTRICITY	155	155	155	155
COAL	9.8	13.0	13.6	16.7
OIL	38.9	67.9	76.4	111
GAS	22.7	29.1	31.6	40.7
LIQUID BIOFUELS	183	183	183	183
PRIMARY SOLID BIOFUELS	56.9	56.9	56.9	56.9
RENEWABLE MUNICIPAL WASTE	56.9	56.9	56.9	56.9
BIOGASES	56.9	56.9	56.9	56.9
NON RENEWABLE WASTE	56.9	56.9	56.9	56.9

Table 8
Emission activity ratio assumed [83].

	Emission rate
	kt_{CO2}/GWh
COAL	0.338
OIL	0.264
GAS	0.201
ELECTRICITY IMPORT	0.226
NON RENEWABLE WASTE	0.148

2.4. Scenario setting

After the definition of the energy system model, two main analyses are performed.

- Representative days (RDs) sensitivity analysis
- Techno-economic optimization of the detailed energy system

Fig. 5 summarizes the structure of this work and the scenarios that have been analyzed.

2.4.1. Representative days sensitivity analysis

A sensitivity analysis is proposed to investigate the influence of the variation in the number of representative days on both the model results and the computation time. As the number of RDs increases, the computational cost increases, while the model results become more refined and less approximate. Therefore, it is necessary to determine the optimal number of representative days as a trade-off between computation cost and accuracy of results.

A simplified model of the Italian power sector is implemented with only batteries as new energy storage option. Moreover, the model period is set from 2021 to 2040. These two simplifications have been made to limit the model's complexity and avoid excessive computational effort. The energy system model is then run several times varying the number

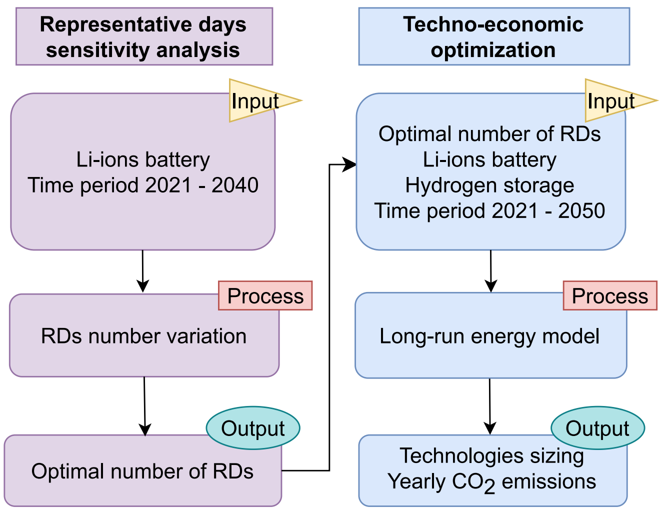


Fig. 5. Procedure scheme of the performed analyses.

of representative days. For the definition of the RDs (through the k-means clustering process), the time series of the capacity factor of onshore wind and PV technology and the time series of electricity demand are considered.

The number of RDs is varied from 6 to 144 (due to the high computational cost, no results are obtained with 365 RDs). Results are then investigated and compared as a function of the number of representative days, focusing on the problem resolution time, the objective function (i.e., total net present cost), and the sizes of the involved technology.

2.4.2. Techno-economic optimization

The aim of the techno-economic optimization analysis is to carry out a long-term planning of the Italian power system from 2021 to 2050 and investigate the role of renewable technologies and energy storage systems. The main characteristics of the optimization framework (in terms of decision variables, objective function, contraints and results) can be summarized as follows.

2.4.2.1. Decision variables.

- Annual installed capacity of *technologies* and *storages* in each *year*.
- Activity of *technologies* and *storages* in each time interval.

2.4.2.2. Objective function.

- Minimization of the net present cost (NPC) of the energy system, given by the sum of the discounted costs (including capital, fixed and variable terms) of *technologies* and *storages* over *regions* and *years*.

2.4.2.3. Constraints.

- Carbon phase-out by 2025 of fossil fuel-based technologies, with exception of natural gas power plants, which can still be considered in the future Italian energy mix [64].
- PNIEC trends of bio-fuels, hydropower and geothermal power plants are imposed [64].
- Onshore wind *soft* case potential and offshore wind potential are set (see Section 2.3.2).
- Photovoltaic *soft* case potential is set (see Section 2.3.2).
- Hydrogen system (composed by electrolyzer, fuel cell and hydrogen tank) and Li-ion battery are considered as storage technologies.

2.4.2.4. Results.

- Total system costs (in terms of net present cost, NPC).
- Optimal configuration of the energy system and its evolution over the years.
- Share of electricity generation from technologies.
- CO_2 emissions.

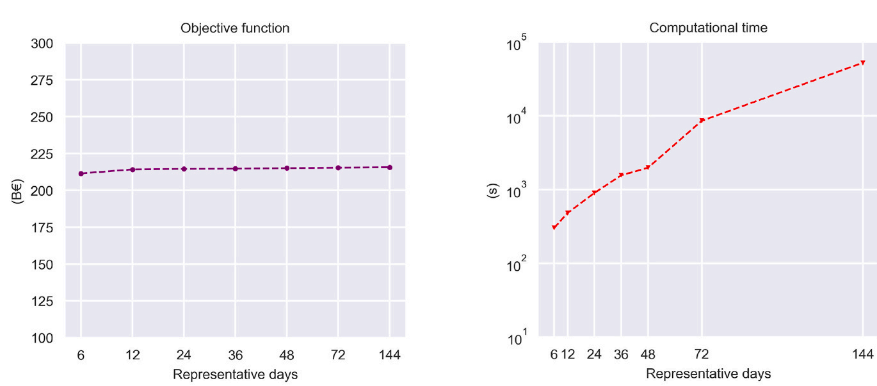
3. Results and discussion

3.1. Representative days impact

The representative days sensitivity analysis was performed using the simplified battery-only scenario from 2021 to 2040, varying the number of RDs from 6 to 144. The full scale solution, which includes all days of the year, was not performed due to the high computational cost.

The best trade-off between the computational effort and the solution accuracy was derived by analyzing the main sizing results as a function of the number of RDs.

The variation of the objective function with respect to the number of RDs is shown in Fig. 6(a). The NPC tends to converge as the number of RDs increases, with a variation of only 1.93 % between 6 and 144 RDs.



(a) (b)

Fig. 6. (a) Objective function and (b) computational time as a function of the number of representative days.

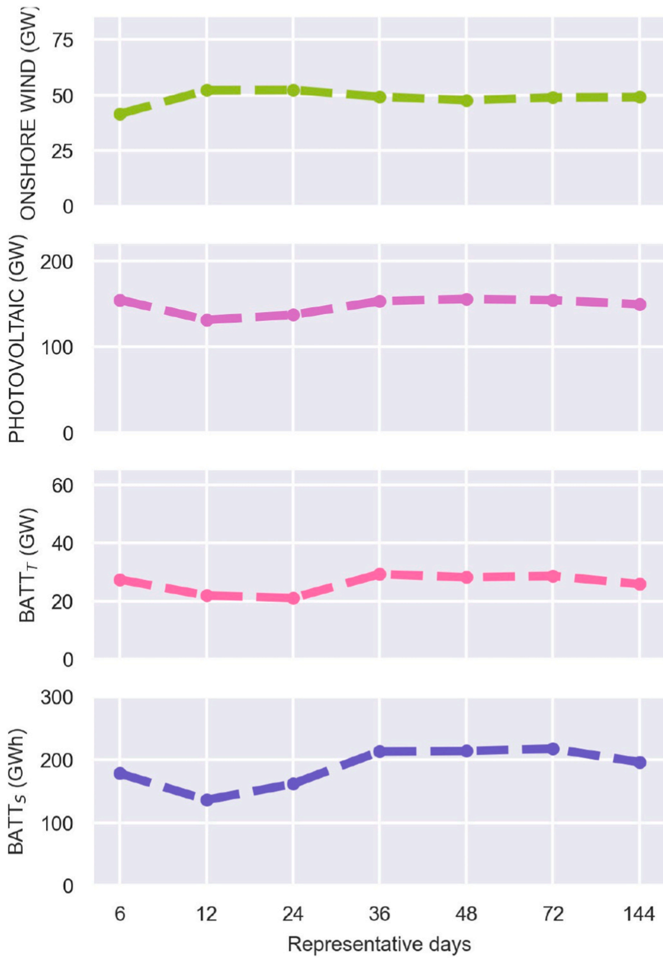


Fig. 7. Sizing results of the VRES and energy storage technologies as a function of the number of representative days. Results refer to the year 2040.

Fig. 7 shows the sizing outcomes of the VRES and energy storage technologies in the year 2040 as a function of the number of RDs: onshore wind capacity, photovoltaic capacity, battery capacity in terms of power ($BATT_T$) and energy ($BATT_S$) components. The different results show quite a stable behavior when the number of RDs is varied. The variation between the results of installed capacity in 2040 obtained with 6 RDs and with 144 RDs is 15 % for the onshore wind technology, 3.5 % for the photovoltaic technology, 6.19 % for the battery power component, and 9.15 % for the battery energy component. Finally, the computational time is analyzed as a function of the number of RDs (Fig. 6(b)): as the number of RDs increases, the data processing also increases. The vertical axis is shown in logarithmic scale, resulting in an exponential trend. In particular, the computation time increases from 300 s with 6 RDs to 52,680 s with 144 RDs. Therefore, the use of RDs significantly reduces the computational cost of the problem.

Considering these results, 6 RDs guarantee a reasonable level of result accuracy and computational effort suitable for complex scenarios with a large amount of input data to be optimized.

3.2. Techno-economic optimization results

The techno-economic long-term analysis by 2050 was performed considering 6 RDs (30 time slices). The detailed model of the Italian power sector was also run considering a higher number of RDs, but it was not possible to obtain any results due to the increased computational burden. The model, indeed, covers a time horizon from 2021 to 2050, and includes the hydrogen-based energy storage system (i.e., electrolyzer, fuel cell and hydrogen tank) as well as the offshore wind capacity factor time series for the RDs definition, which strongly increases the amount of data input to be elaborated. Anyway, as previously demonstrated for a simplified case study, the use of 6 RDs was found to provide accurate sizing results, with a small error on the objective function compared to the case with 144 RDs. From the techno-economic optimization, an objective function of 233.7 B€ was found as NPC for the whole power sector.

Nevertheless, it must be emphasized that this study focuses on the power system and therefore the sizing outcomes relate specifically to this sector. A single-node approximation is also used, limiting the consideration of bottlenecks in electricity transmission.

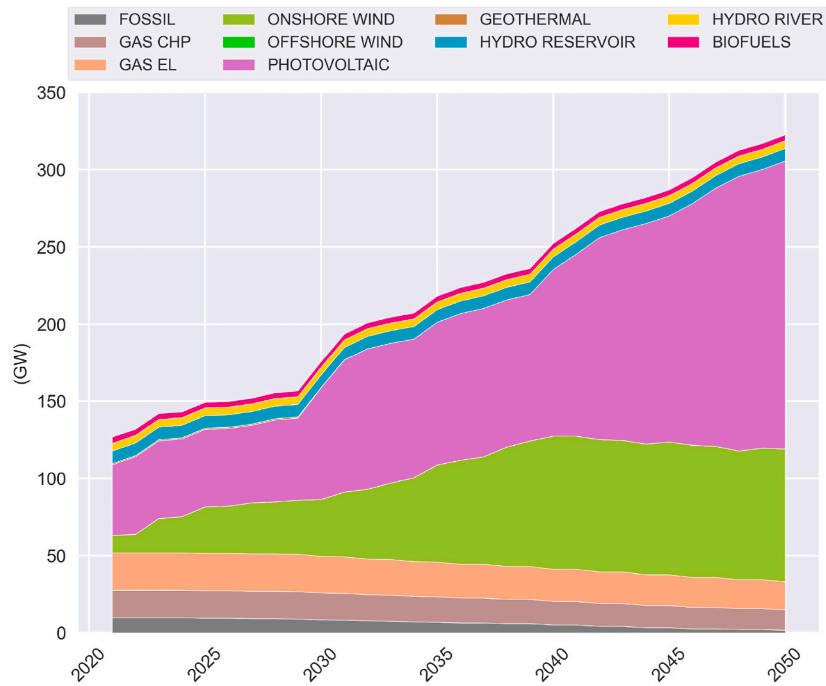
Sections 3.2.1 and 3.2.2 show the main outcomes of the model optimization, in terms of technologies sizing and yearly CO_2 emissions, respectively.

3.2.1. Technologies sizing

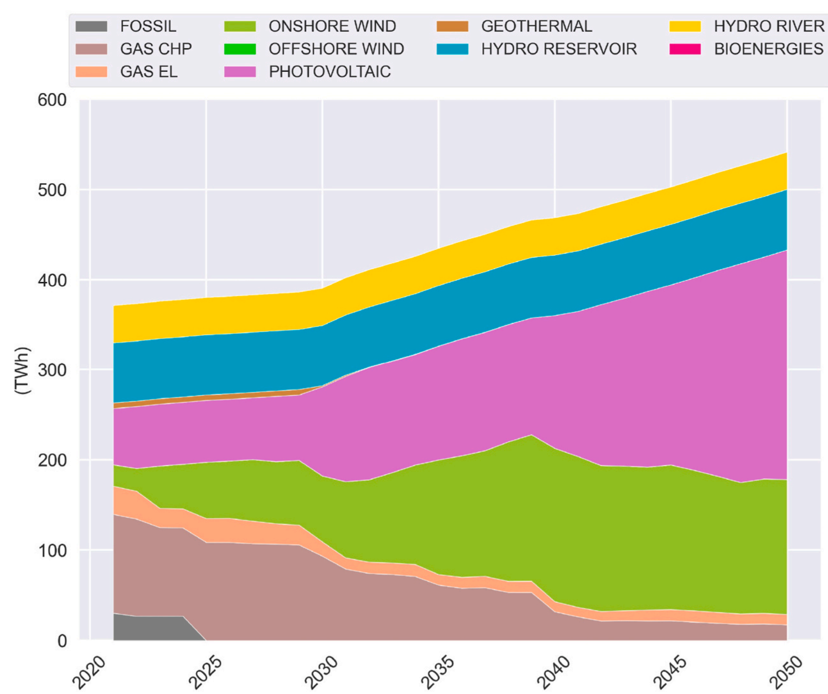
Fig. 8(a) presents the evolution across the model period of the installed capacity of each technology, which is composed by new and residual capacities. Onshore wind and photovoltaic technologies experience a huge increase up to 86.2 GW and 186.7 GW, respectively, by 2050. Fossil fuel- and natural gas-based power plants face a reduction over the years, although their dispatch share of 20 % is ensured. Since there was no size constraint on fossil fuel-based technologies, the high share of VRES capacity (which increases over the years of the model period) is an indication of the cost-effectiveness of VRES technologies in generating electricity. Furthermore, the total share of VRES capacity in 2050 is about 84.6 %, which is quite in line with other studies, e.g., 57 % of VRES share by Colbertado et al. [18] and 80 % by Jafari et al. [20].

Fig. 9(a) and (b) show the installed capacity (new and residual) of storage facilities, in particular of power components (in GW) and of energy components (in GWh), respectively. The installed capacity of the battery technology (in terms of power) increases sharply in the first part of the model time period, due to its lower cost and higher efficiency with respect to the hydrogen storage technology, and decreases in the second part of the model time period down to 20.1 GW by 2050. By contrast, the installed capacity of the fuel cell and electrolyzer systems is expected to have an important increase in the last part of the considered time horizon, up to 7.53 GW (fuel cells) and 28.9 GW (electrolyzers) by 2050. Furthermore, the installed energy capacity of the battery and hydrogen tank by 2050 is 40.2 GWh (corresponding to an energy-to-power ratio of 2) and 219.6 GWh, respectively. Therefore, batteries are the most cost-effective choice as energy storage solution in the first part of the model period up to the year 2039, when the share of VRES capacity (over the total installed capacities for electricity production), is 60 %. The greater competitiveness of hydrogen storage is shown when the VRES installed capacity enhances further, up to 84.6 % in 2050, thanks to the presence of low-cost high-capacity hydrogen tanks. It is also highlighted the key role of energy storage systems in limiting the oversizing of the renewable technologies, as also observed by both Jafari et al. [20] and Marocco et al. [84].

Fig. 8(b) shows the evolution of electricity production by technology over the model period. The main contribution is given by renewable energy systems, in particular photovoltaic, onshore wind, hydro reservoir and hydro run of river technologies. Instead, the production share of fossil fuel-based and natural gas-based power plants decreases in time. In particular, Fig. 10(a) illustrates the share of the various technologies for the electricity production by 2050: VRES accounts for 74.6 %, hydro power for 20.1 % and natural gas-based power plants for 5.3 %. The VRES term includes the photovoltaic (63.0 %) and onshore wind (37.0 %) technologies. The increasing electricity production from VRES over the years is the direct result of the higher installed VRES capacity achieved by optimizing the long-term planning of the Italian power system (through the minimization of the NPC). In particular, the final VRES penetration in meeting the electricity demand of Italy in 2050 is in line with the VRES share in the electricity production reported in other



(a)

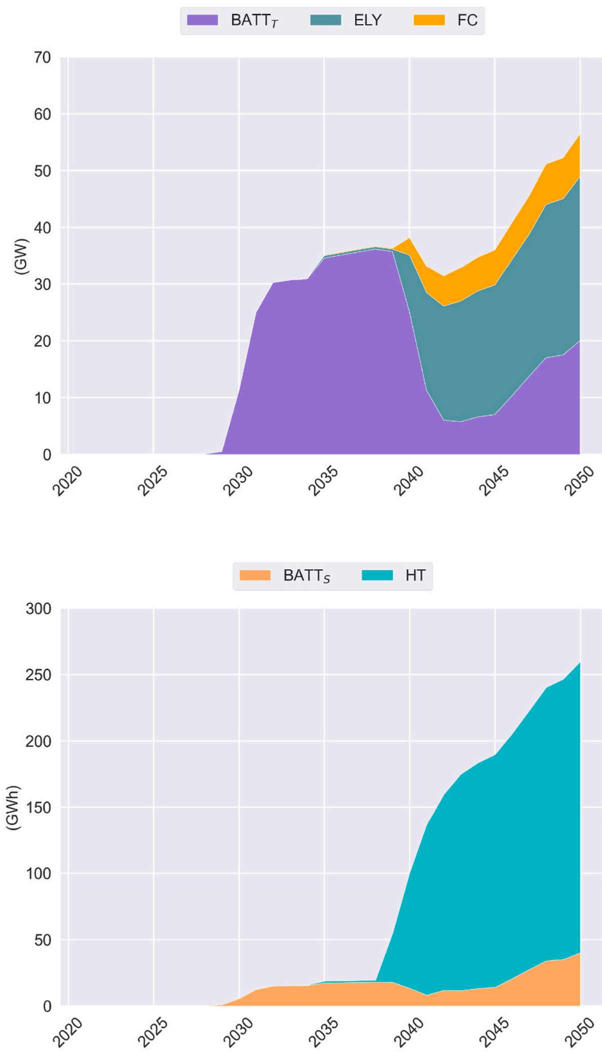


(b)

Fig. 8. (a) Annual capacity by technology from the techno-economic optimization analysis; (b) Annual production by technology from the techno-economic optimization analysis.

studies [20,21]. Nevertheless, it should be noted that, in contrast to these studies, the present work has carried out an assessment for the Italian electricity system to explore its optimal capacity expansion planning from 2021 to 2050.

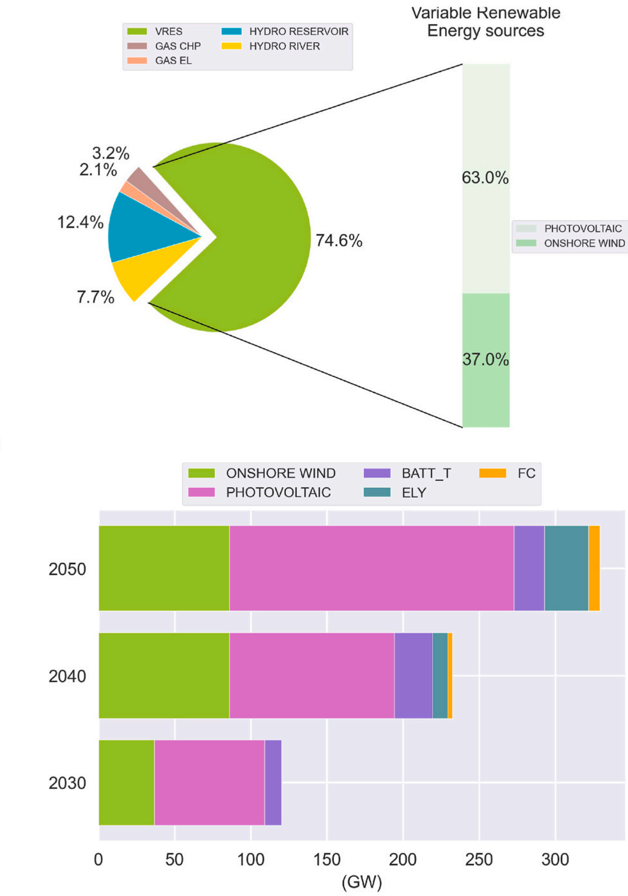
Fig. 10(b) presents the total installed capacity (i.e., new and residual) of VRES and storage facilities for three reference years (2030, 2040, 2050). Comparing the years 2030 and 2050, onshore wind and photovoltaic systems increase from 36.8 GW to 72.4 GW by 2030, to 86.2 GW and 186.7 GW by 2050, respectively. About 11.2 GW of battery are installed by 2030 with a peak of 36.2 GW by 2038, although there is a sharp decline to 20.1 GW by 2050. This is due to the important expansion of hydrogen storage, where the capacities of the electrolyzer and fuel cell technologies increase from 10.03 by 2040 to 28.9 GW by 2050, and from 3.06 GW by 2040 to 7.53 GW by 2050, respectively. It is interesting to see that there is a correspondence between the increasing percentage of installed VRES capacity and storage facilities. By 2030,



(a)

(b)

Fig. 9. (a) Annual capacity of storage technologies in terms of power (battery power component, electrolyzer, and fuel cell); (b) Annual capacity of storage technologies in terms of energy (battery energy component, and hydrogen tank).



(a)

(b)

Fig. 10. (a) Electricity production by 2050 with the different technologies share; (b) Total annual capacity of VRES and storage facilities by 2030, 2040 and 2050.

with 109.1 GW of installed VRES capacity, only battery storage is installed; by 2040, with 194.3 GW of installed VRES capacity, hydrogen storage is also installed; and finally by 2050, with 272.9 GW of installed VRES capacity, there is a decrease in battery capacity and a significant increase in hydrogen storage capacity.

The analysis of the decarbonization of the Italian power sector shows that an important shift is needed from the current energy mix, which relies heavily on fossil fuel-based technologies, to an opposite configuration strongly based on renewable energy sources. Indeed, the VRES capacity of 272.9 GW can lead to electricity production of around 400 TWh by 2050. This result is consistent with the analysis of the Italian case study by Gaeta et al. [85] in which a VRES electricity generation from solar and wind resources of 440–550 TWh is required to meet electricity demand and ensure a green transition.

3.2.2. *Yearly CO_{CO2} emissions*

CO_2 emissions over the entire time horizon of the model are shown in Fig. 11. Emissions face a strong decrease of 87.3 %: from 79.1 Mt_{CO2} in 2021 to 10.1 Mt_{CO2} in 2050, due to the high penetration of renewable technologies in the power system. It is noteworthy that, by performing a techno-economic optimization without environmental constraints, CO_2 emissions in the power sector already fall sharply from 2021 to 2050, which is associated with a 5-fold increase in VRES capacity compared to 2021.

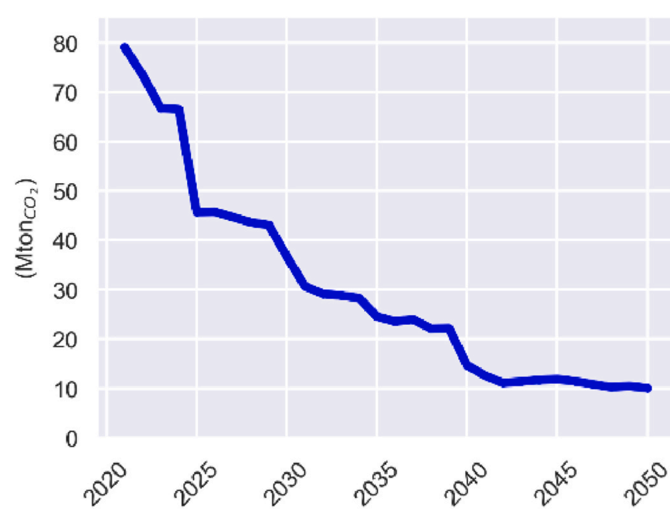


Fig. 11. CO_2 annual emissions.

4. Conclusions

In this work, an updated version of the OSeMOSYS tool is used to perform an optimal long-term planning of the Italian power sector. A time series clustering approach is applied, considering time varying input data, such as the time series related to VRES capacity factors and electricity demand. The aim is to provide an adequate temporal representation and description of the VRES, and thus obtain a reliable sizing of the involved technologies. Besides, the potential assessment of both the onshore wind and photovoltaic technologies is performed, to provide accurate capacities constraints to the model.

First, a sensitivity analysis on the number of RDs is carried out to investigate both the accuracy of results and the impact on the computational effort. It is observed that the variation between the results obtained with 6 RDs and 144 RDs is limited, with a divergence for the objective function equal to 1.9 %. On the contrary, the computational time increases of two order of magnitude between 6 RDs and 144 RDs. Considering these results, 6 RDs are selected for the long-term analysis of the Italian electricity system, due to its complexity and the large amount of input data, ensuring an adequate level of accuracy at a planning stage.

The techno-economic optimization analysis of the Italian power sector yields an NPC of 233.7 B€, resulting in a high penetration of VRES technologies in the energy mix by 2050. Indeed, by 2050, the total VRES capacity is 272.9 GW, composed of photovoltaic (68 %) and onshore wind (32 %) technologies. Offshore wind is not installed due to its high investment costs, although it has a higher capacity factor with respect to onshore wind. On the electricity production side, a VRES share of 74.6 % by 2050 is planned, while the remainder is divided between hydropower (20.1 %) and gas-based technologies (5.3 %).

Furthermore, this analysis highlights the key role of energy storage facilities in promoting energy systems strongly based on VRES. In particular, battery storage is the preferable storage solution in the first part of the power sector transition, due to its lower investment costs and higher efficiency compared to hydrogen storage. As VRES penetration increases over the years, hydrogen storage becomes pivotal, as it is economically favorable as a long-term storage solution, though its round-trip efficiency is lower compared to the battery solution.

Finally, a high VRES share in the power system leads to a strong reduction in CO_2 emissions over the model period, up to approximately 87 %. It is worth noting that these results were achieved without imposing any decarbonization measures (in terms of CO_2 constraints) and are due to the expected future cost decline of VRES and storage technologies.

Future works could extend this analysis to other sectors such as heat, transport and industry. Besides, energy interactions with border countries could be further explored, allowing for a more cost-efficient solution for the future Italian power sector.

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.ijhydene.2024.01.358.

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