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100% renewable energy Italy: A vision to achieve full energy system decarbonisation by 2050

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ABSTRACT

This paper explores the potential for a 100% renewable energy system in Italy by 2050, investigating alternative strategies to decarbonise hard-to-abate sectors and provide system flexibility. The aim is to evaluate implications, reciprocal effects and synergies between these strategies. The outcomes demonstrate the potential of power-to-X technologies in balancing non-dispatchable generation and reducing biomass consumption. Around 90% of electricity production can come from photovoltaics and onshore and offshore wind. Energy savings, district heating deployment along with electrification of building stock and light transport, by means of heat pumps and electric vehicles, have been considered as key measures. Different application strategies for alternative fuels, such as hydrogen, biofuels and electrofuels, in heavy-duty transport and industry have a significant impact on the configuration of the entire energy system. In scenarios with high hydrogen demand, the power-to-gas strategy allows less reliance on electricity storage systems. Biomass availability emerges as a critical factor, affecting the sustainability of the energy system. A highly flexible demand-side approach offers energy and economic advantages. This study demonstrates the technical and economic feasibility of a carbon neutral energy system in Italy, while acknowledging the challenges towards the full decarbonisation and emphasising the importance of integrated energy planning.

1. Introduction

One of the greatest challenges for humanity in the coming decades is to mitigate the potential impacts of human-induced climate change. Short- and long-term risks of climate emergency can cause irreversible damage to nature and people [1].

The 2015 Paris Agreement sets the goal of keeping the global average temperature increase well below 2 °C above pre-industrial levels and to continue efforts to limit it to 1.5 °C [2].

A strong commitment from all countries is needed to decarbonise energy systems as quickly as possible. However, despite this need being widely shared by governments and national and international policies, fossil fuel consumption has been steadily increasing in recent years [3].

Furthermore, the recent energy crisis has highlighted the need for importing countries to reduce their fossil fuel consumption and rely on the domestic energy sources [4]. Such energy crisis may represent an opportunity to speed up the transition to 100% renewable energy systems [5]. On the other hand, there is also the risk of focusing too much on import diversification and expanding fossil fuel infrastructure [6]. Such long-term investments represent stranded assets that may delay or hinder the transition to climate-neutral energy systems [7].

Several countries have set targets for complete decarbonisation in the coming decades. The European Union has set the goal of being climate-neutral by 2050, committing to an intermediate emission reduction target of 55% by 2030 [8]. Italy, in turn, has defined a long-term strategy to achieve the national energy system decarbonisation by 2050 [9].

Research around 100% renewable systems has grown substantially in the recent past and many studies have shown its feasibility [10]. Several works and international reports show that the electricity system decarbonisation is already economically viable [11]. Moreover, the energy crisis has increased the generation costs from thermal power plants and allowed renewable sources, such as wind and solar photovoltaics, to generate electricity at much lower costs [12].

Much attention in research on 100% renewable system planning is given to the electricity system integration with the whole energy system in order to accommodate non-dispatchable generation [13]. In future renewable systems, Power-to-X strategies will play a key role in

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converting renewable electricity into other carriers or applications [14]. The electricity conversion allows to store critical excess electricity production (CEEP) at a lower cost than electrochemical storage, to minimise the use of electric batteries (EBs), characterised by a high life-cycle environmental impact, and to decarbonise other energy sectors [15]. As pointed out by Lund et al. [16], exploiting synergies between different energy sectors makes it possible to achieve a better configuration of the energy system than separate optimisation of each individual sector.

The Power-to-Heat strategy is based on the electricity conversion into thermal energy by means of heat pumps (HPs) [17]. This allows to increase demand flexibility and exploit thermal storage for balancing variable renewable generation [18]. Great interest in the last decade has been held by the Power-to-Gas strategy, which allows the electricity conversion into green hydrogen by means of the water electrolysis process [19]. Hydrogen can then either be used directly or further converted into synthetic fuels [20].

Some hard-to-electrify sectors represent the main barrier to achieving complete decarbonisation of the energy system [21]. The development of alternative fuels is a necessity to enable the renewable penetration in those energy sectors [22].

Biofuels can be a viable option for fuel switching without the need for a radical change of infrastructure [23]. They make it possible to replace fossil fuels while ensuring temperature levels in industry [24]. Furthermore, liquid biofuels represent a mean for the decarbonisation of all transport modes [25]. However, limitations in the biomass production must be considered to ensure the sustainability of the production process. As several studies have shown, the biomass potential is hardly sufficient to completely satisfy the future demand for alternative fuels [26].

Hydrogen represents an interesting solution to integrate different energy sectors and indirectly electrify hard-to-abate energy demand [27]. Applications in industry allow very high temperatures to be reached [28]. Furthermore, applications in mobility are widely investigated, although they are still mostly at a pre-commercial stage [29]. A barrier to the hydrogen deployment is the change of infrastructure and end-users, which represents a very high cost for this strategy [30].

A potential indirect hydrogen application in hard-to-abate sectors is the further synthesis into synthetic fuels [31]. The combination of a hydrogen stream with a carbon source allows the production of both liquid and gaseous synthetic fuels by means of different processes [32]. For instance, methanol has interesting potential for the transport sector applications [33]. The dehydration of methanol allows the production of dimethyl ether (DME), a non-toxic and non-carcinogenic compound that is a suitable substitute for fossil fuels in internal combustion engines [34].

In recent years, the different decarbonisation technologies have been separately analysed. However, a holistic view is needed in energy planning studies to analyse the integration of the alternative fuel value chains with the whole energy system and especially with renewable generation [35].

1.1. Literature review

In recent times, there has been a notable increase in research into 100% renewable energy systems. This has led to the accumulation of a growing body of evidence attesting to the feasibility of these systems.

One of the most studied countries in the transition to a decarbonised energy system is Denmark. As early as 2009, Lund and Mathiesen analysed Denmark's energy transition towards full decarbonisation by 2050 and developed an intermediate scenario by 2030 [36]. In 2015, Mathiesen et al. developed a new strategy for achieving a 100% RE system based on a smart energy system approach [37]. More recently, a new planning study for a fully decarbonised Danish energy system in 2045 has been presented by Lund et al. [38].

The same research group developed a seven-step strategy for configuring 100% renewable systems and applied it to the Irish energy system [39].

That step-by-step approach to energy system decarbonisation process has been implemented and applied to achieve a zero emission system in the European Union [40]. That study provided a comparative analysis of different strategies for meeting heat demand. The extensive use of HPs for both individual and district heating (DH) was found to be the best choice.

Dominiković et al. [41] proposed a vision for the achievement of a carbon-neutral energy system within the South-eastern European region by 2050. The approach they propose emphasises the extensive use of hydropower, facilitates the widespread use of pumped storage and limits the use of biomass. Electrofuels are mainly intended for heavy transport.

A study conducted by Child and Breyer [42] examined the potential of 100% renewable energy in the Finnish energy system. In that study, geographical location and the high seasonal variability of production are of great importance, influencing the system configuration and using power-to-gas technologies as the main solution to facilitate long-term energy storage. In contrast to other studies, hydrogen plays a central role in ensuring system flexibility over both short- and long-term horizons.

Hansen et al. [43] have analysed the transition of the German energy system to 100% renewable energy by 2050. Their comprehensive study examines the different energy sectors and identifies potential synergies between them. In detail, the work deals with heavy transport, evaluating four alternative scenarios: hydrogen via fuel cells, direct electricity, CO2 electrofuels and bio-electrofuels. A key criterion in the selection of scenarios is the biomass consumption threshold. This study is one of the few that analyses alternative scenarios in the sectors. However, it only employs this approach on the transport sector without investigating the reciprocal effects between the strategies on the different sectors.

The energy planning of the Italian national energy system has been the subject of only a few works in the literature.

Bellocchi et al. [44] have developed a model of the Italian energy system on EnergyPLAN and applied it to investigate the role of electric vehicles (EVs) in the integration of increasing shares of renewable generation. Their subsequent work [45] have used this model to investigate the potential for system flexibility offered by EVs in combination with the electrification of the heating sector in Italy. Those works do not analyse the complete decarbonisation of the Italian energy system.

Prina et al. [46] have developed a bottom-up, long-term optimisation model combining EnergyPLAN with a multi-objective evolutionary algorithm. That work, as it is aimed at developing a new optimisation tool, analyses the deployment of certain capacities in different scenarios, without investigating strategies for the complete decarbonisation of all sectors.

Gaeta et al. [47] have proposed a roadmap for a fully decarbonised Italian energy system. However, their work has been developed with the TIMES model, in which the system is investigated without considering an hourly resolution of the simulation.

The authors of this paper have previously analysed the Italian energy system in a study that developed a methodology to improve the national energy strategy in order to reduce greenhouse gas emissions by at least 55% by 2030 [48].

There are some studies in the literature that consider Italy's national energy system, however, there is a lack of a study for planning a 100% renewable system that considers all sectors, using simulation software such as EnergyPLAN, which features numerous Power-to-X technologies and hourly resolution.

Recently, Hansen et al. [49] have analysed the status and perspectives of research in the 100% renewable energy system planning. The study analysed and compared 180 articles published since 2004. Many works concern only the electricity sector, and the review shows the need for a holistic approach in modelling 100 % renewable energy systems. In addition, less than 20 % of works propose a comprehensive analysis of all energy sectors.

In Ref. [50], the main authors who have investigated in the last decades 100% renewable systems have provided an overview of the evolution and findings within the research field of 100% renewable energy systems. Several methodological milestones were identified, including the differentiation between local, national, and global perspectives, the use of hourly temporal resolution, and the consideration of entire energy systems. Many studies indicate that more than 90% of electricity supply can come from solar PV and wind power, but fewer reach at least 80% of total primary energy demand. Their main conclusion is that most studies in this field suggest that 100% renewable energy systems are not only feasible but also cost-effective, providing a key pathway to a sustainable future without reliance on fossil fuels.

1.2. *Scope of the work*

The aim of this paper is the analysis of different configurations for the Italian energy system decarbonisation by 2050, investigating the feasibility of a 100% renewable energy system based on domestic RES. In detail, the objective is to investigate different strategies for decarbonising the hard-to-abate sectors and to provide system flexibility through a combined approach, by assessing their implications, reciprocal effects and synergies between them.

As highlighted in the literature review, few works analyse the complete decarbonisation of all energy systems, integrating them in the same model. The novelty of this study therefore lies in the innovative approach related to the combined analysis of the effects of the application of alternative strategies on different sectors. This makes it possible to identify the actual potential of the strategies in relation to the whole system and the interactions between the solutions adopted.

Furthermore, this paper presents the analysis of a 100% renewable energy system in a country such as Italy characterised by high full load hours of PV and limited wind power potential.

Finally, this paper applies the MATLAB Toolbox for EnergyPLAN (MAT4EnergyPLAN) for the optimisation of energy system configurations and the renewable generation mix, presenting a methodology for the comparative analysis of decarbonisation strategies. Although EnergyPLAN is one of the most widely used software tools for national energy planning, the application of the MAT4EnergyPLAN to 100% renewable energy systems on a national scale is, to the best of the author's knowledge, not found in the literature.

Section 2 presents the methodology for the investigation and describes the reference model. In Section 3, the decarbonisation scenarios for the Italian energy system have been outlined. Then, Section 4 shows and discusses the analysis results. Finally, Section 5 summarises the main findings of the work.

2. Material and methods

In the present work, different scenarios for the complete decarbonisation of the Italian energy system have been analysed.

Applying a bottom-up approach, the demand of the different energy carriers in the 100% renewable system has been defined for the different scenarios. Starting from a reference model of the current Italian energy system, the complete decarbonisation has been modelled by applying several solutions for the different energy sectors, as described in detail in Section 3.

Some strategies, such as energy saving measures and deep end-use electrification, have been considered in all the scenarios. Furthermore, alternative solutions for decarbonising hard-to-abate sectors and providing demand-side flexibility have been proposed. In detail, 3 scenarios for the decarbonisation of heavy transport, 2 scenarios for the decarbonisation of industry and 2 flexible demand scenarios have been developed. By combining the possible configurations, 12 decarbonisation scenarios have been identified.

Afterwards, the identification of renewable energy sources (RES) and EB capacity has been carried out by means of a multi-objective optimisation process through the MAT4EnergyPLAN tool. PV, onshore and offshore wind and EB capacity have been considered as decision variables, by minimising both annual costs and CEEP.

The different 100% renewable energy system configurations have been defined and compared by assessing energy, environmental and economic aspects.

In Fig. 1, the methodology applied in the present work has been graphically illustrated.

2.1. *EnergyPLAN and Mat4EnergyPLAN*

EnergyPLAN is a computer tool designed by Aalborg University to model and simulate energy systems with high RES shares [51]. Suited for exploring sector coupling strategies, it encompasses various energy conversion systems, storage options, and energy sectors. The software employs dynamic systems with high temporal resolution (i.e. hourly) to compute energy balances related to different energy sectors.

More than three hundred case studies have been conducted by means of this energy modelling tool in the last years [52]. EnergyPLAN has been used to analyse several scales. The main level of analysis concerns the decarbonisation of national energy systems. Moreover, there are many papers in literature applying EnergyPLAN at local, district or multi-country level. Furthermore, according to Ref. [50], this tool turns out to be the most used software for the analysis of 100% renewable energy systems.

EnergyPLAN is characterised by very short computational times, which allows a high number of simulations of a complex system to be performed in a short time. Therefore, this software lends itself to coupling with other tools, especially for performing combined simulations or implementing optimisation processes.

The MATLAB Toolbox for EnergyPLAN (MaT4EnergyPLAN) has been recently developed [53]. MaT4EnergyPLAN is a set of functions developed to work with the EnergyPLAN software using MATLAB. This tool enables to harness the energy system analysis capabilities of EnergyPLAN while benefiting from the computational advantages of MATLAB. The main advantage is the large number of EnergyPLAN simulations, which can be easily managed by means of the MATLAB environment. Despite its recent release, MaT4EnergyPLAN has already found applications in various works [54,55].

2.2. *Multi-objective optimisation process*

The identification of RES and EB capacity has been carried out by means of a multi-objective optimisation process. A Pareto-based multi-objective optimisation approach to identify the most suitable scenarios has been applied.

The mathematical representation of this multi-objective problem is as follows:

$$\textit{minimise}: y = f(x) = (f_1(x), f_2(x), \ldots, f_k(x)) \tag{1}$$

$$\textit{subject to}: g(x) = (g_1(x), g_2(x), \ldots, g_m(x)) \leqslant 0$$

$$h(x) = (h_1(x), h_2(x), \ldots, h_p(x)) = 0$$

$$l_i \leqslant x_i \leqslant u_i,\ i = 1, 2, \ldots, n$$

$$\textit{where}: x = (x_1, x_2, \ldots, x_n) \in X$$

$$y = (y_1, y_2, \ldots, y_k) \in Y$$

Here:

- x represents the decision variables, bounded within the range defined by lower limits (l_i) and upper limits (u_i);
- y consists of k objective functions;
- X denotes the decision space, comprising all possible x vectors;
- Y represents the objective space;

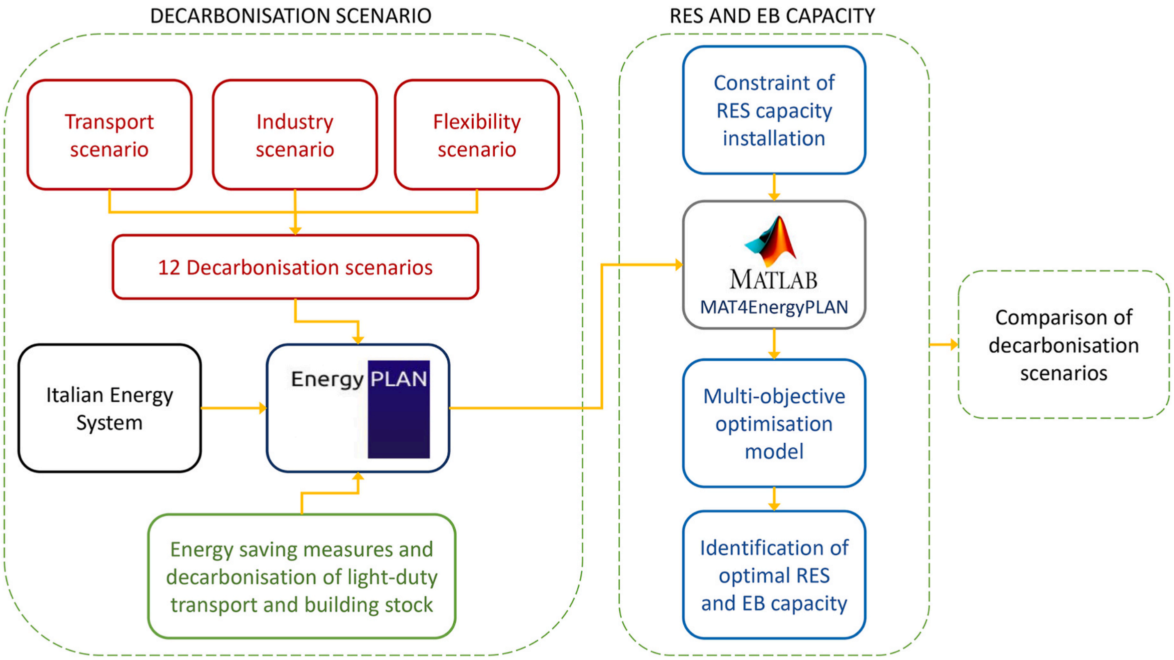


Fig. 1. Graphical methodology.

- $g(x)$ represents a set of inequality constraints;
- $h(x)$ indicates the set of equality constraints.

The Pareto solutions are defined by the following dominance rule (Equation (2)):

$$\begin{cases} f_i(x) \leq f_i(x'), \forall i \in \{1, 2, \cdots, m\} \\ f_i(x) < f_i(x'), \exists i \in \{1, 2, \cdots, m\} \end{cases} \tag{2}$$

To evaluate the most suitable scenario on the Pareto front, the Utopia point (UP) is determined. The UP represents an ideal but unfeasible solution that achieves the best values for the given objectives. Specifically, in a two-objective minimisation problem, the UP is a point with the best values on both axes. The distance between the normalized objective function and the UP ($P_{solution}$) is calculated using Equation (4), where $f_{jUtopia}$ represents the minimum allowed value for the normalized objective function j, and f_j is the current value of the normalized objective function j. The scenario characterized by the minimal distance from the UP is considered the most suitable scenario.

$$\min(P_{solution}) \tag{3}$$

$$P_{solution} = \sqrt{\sum_j \left(f_{jUtopia} - f_j\right)^2} \tag{4}$$

In the present work, four decision variables have been optimised in order to find the optimal configuration for every scenario.

The four decision variables are:

- PV capacity (GW)
- Onshore wind capacity (GW)
- Offshore wind capacity (GW)
- Electric battery capacity (GWh)

Furthermore, the objective function aims to minimise the following indicators:

- Total annual costs (G€/yr)
- Critical excess electricity production (TWh/yr)

2.3. Reference model

The EnergyPLAN reference model of the Italian energy has been developed and applied for previous works [12,48]. Most of the inputs have been defined according to Eurostat data and information from national documentation [56–59]. A detailed description of the input data is provided in Ref. [12]. Furthermore, such model has been validated by comparing fossil fuel consumption and CO2 emissions with data from Refs. [56,59].

The model validation has been summarised in Table 1.

2.4. Technical and economic assumptions

The main technical and economic assumptions have been summarised in the supplementary material. In detail, Appendix A (Tables SM1-SM4) outlines the technical assumptions, Appendix B (Tables SM5-SM7) defines the cost assumptions and in Appendix C (Figures SM1 and SM2) the cost curves for energy saving measures and DH deployment have been depicted.

Table 1
Validation of EnergyPLAN model: comparison between output model and actual data [12].

Value	Unit	Actual data	EnergyPLAN model	Discrepancy %
Annual CO_{2eq} emissions	Mt_{CO2}/yr	321.59	321.76	+0.05 %
Natural Gas	TWh/yr	708.92	708.69	−0.03 %
Oil and petroleum products (excluding LPG)	TWh/yr	570.31	569.56	−0.13 %
LPG	TWh/yr	27.34	27.30	−0.15 %
Solid fuels	TWh/yr	75.37	75.56	+0.25 %
Non-renewable Waste	TWh/yr	12.03	12.02	−0.05 %

3. Decarbonisation scenarios of the Italian energy system

In this section, the decarbonisation scenarios and the measures considered for each energy sector have been described.

As a first step for the decarbonisation of the Italian energy system, the main measures for decarbonisation considered in the various studies on 100% renewable energy systems in the literature have been taken into account. For some sectors, indeed, the general electrification of final consumption is now established as the main pathway to decarbonisation. However, several solutions have been considered to achieve zero emissions in hard-to-abate sectors. Therefore, some alternative scenarios have been developed and then combined in the following analysis.

A summary of the measures considered for each sector has been presented in Fig. 2.

3.1. Heating

In Italy, heating demand is mainly supplied by decentralised natural gas (NG) boilers.

The literature concerning the decarbonisation of the heating sector is remarkably extensive [60] and, from previous studies, the best actions to implement in order to decarbonise the heating sector more efficiently have been identified. Furthermore, a study dedicated to the Italian heating sector has been developed within the Heat Roadmap project [61].

Heating in residential and commercial sectors can be supplied at low temperatures. Therefore, the best strategy is the general electrification through HPs [62]. Previous energy planning studies apply the approach of providing heat with low temperature DH supplied by central HPs in urban areas and applying individual HPs in areas with low population density.

DH in Italy is currently very underdeveloped and consists of a heat demand of 13.8 TWh. The Heat Roadmap identifies the Italian DH potential as 60% of the total heating demand.

However, a more recent Italian study limits the Italian DH potential to 114 TWh, about 30% of the total heat demand [63]. The estimates of this latest study have been used in order to take in consideration a more conservative choice. In Ref. [61], dedicated cost curves have been developed for estimating the DH network costs in Italy. Furthermore, DH substation costs have been set according to Ref. [42]. The DH system has been considered supplied by central HPs and industrial waste heat. The latter has been considered according to Ref. [63].

Furthermore, energy saving measures have been considered for the building stock, according to Ref. [64]. In that work, an optimal level of energy saving for the building stock in Italy has been identified equal to around 30%. Such values have been considered for the potential reduction in heating demand.

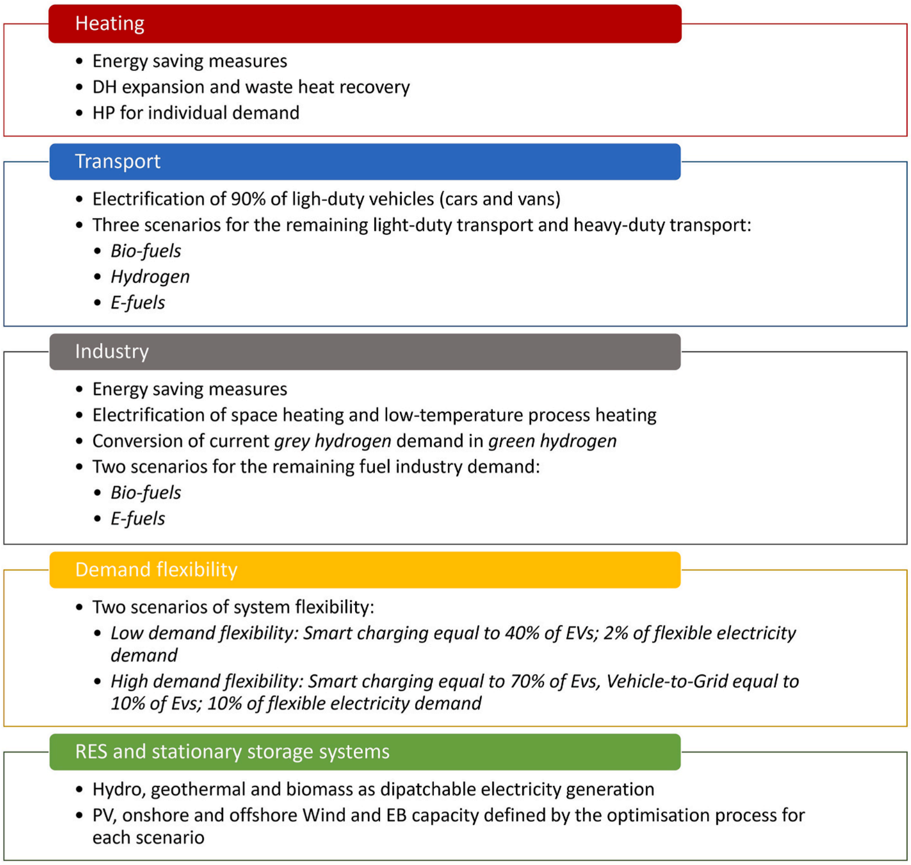
The heating demand not covered by DH has been totally electrified through individual HPs. Nowadays, in Italian rural areas, the use of biomass boilers for heating is still widespread. That solution has been eliminated and replaced by HPs in order to preserve the use of biomass for other sectors where electrification is more complex.

In this study, only one scenario has been developed for heating demand, as the main scientific works on the subject agree that the approach applied is the strategy to be followed for energy planning of heating sector in 100 % renewable energy systems [40].

In Fig. 3, the heating demand in 2019 and by 2050 has been depicted.

3.2. Transport

The transport sector accounts for 31% of the Italian energy system emissions in 2019 [65]. Different actions can be taken for decarbonisation. As a first solution, the conversion of 90% of light-duty private and commercial vehicles has been considered. Transport demand has



Heating
- Energy saving measures
- DH expansion and waste heat recovery
- HP for individual demand

Transport
- Electrification of 90% of ligh-duty vehicles (cars and vans)
- Three scenarios for the remaining light-duty transport and heavy-duty transport:
  - *Bio-fuels*
  - *Hydrogen*
  - *E-fuels*

Industry
- Energy saving measures
- Electrification of space heating and low-temperature process heating
- Conversion of current *grey hydrogen* demand in *green hydrogen*
- Two scenarios for the remaining fuel industry demand:
  - *Bio-fuels*
  - *E-fuels*

Demand flexibility
- Two scenarios of system flexibility:
  - *Low demand flexibility: Smart charging equal to 40% of EVs; 2% of flexible electricity demand*
  - *High demand flexibility: Smart charging equal to 70% of Evs, Vehicle-to-Grid equal to 10% of Evs; 10% of flexible electricity demand*

RES and stationary storage systems
- Hydro, geothermal and biomass as dipatchable electricity generation
- PV, onshore and offshore Wind and EB capacity defined by the optimisation process for each scenario

Fig. 2. Summary outline of measures for the Italian energy system decarbonisation and alternative scenarios considered.

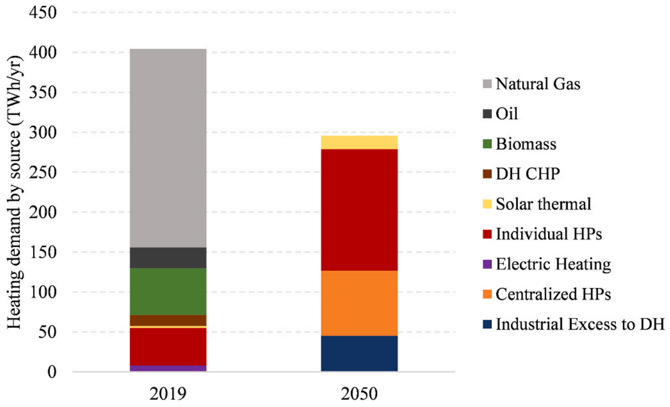


Fig. 3. Heating demand in 2019 and by 2050.

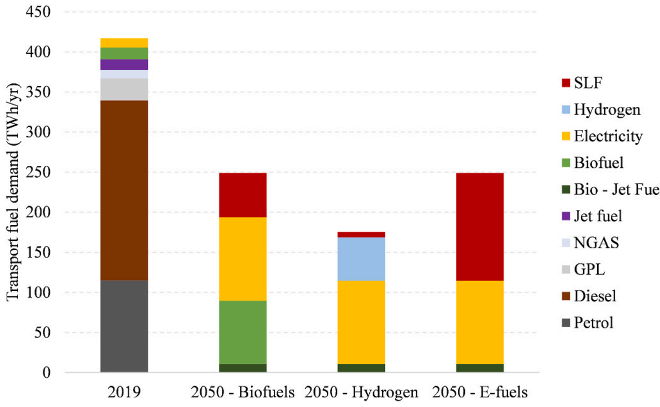


Fig. 4. Transport demand in 2019 and in the different 2050 scenarios.

been assumed to be constant and only active decarbonisation measures have been considered. Assumptions on vehicle specific fuel consumption have been summarised in Table SM4 of the supplementary material.

Electricity infrastructure costs have been calculated according to the correlation developed by Bellocchi et al. [45].

$$C_{EV_{infrastructure}} = 10^4 \bullet EV_{share} + 50 \quad (M€) \tag{5}$$

Rail transport in Italy is mostly electrified. A small part of the train fleet is powered by diesel and complete electrification has been considered.

Three different scenarios have been elaborated for fuel demand in the remaining light-duty transport (cars and vans) and heavy-duty transport (trucks, busses and naval transport):

- Biofuels
- E-fuels
- Hydrogen

The Biofuel scenario concerns the conversion of existing demand for transport fuels into biofuels. In detail, diesel and petrol vehicles are converted into biodiesel and bioethanol, respectively. The efficiency of the biodiesel and ethanol production process has been assumed to be 39.3% and 41.1%, respectively [66]. Furthermore, vehicle efficiencies were not changed compared to the current fossil-fuel based scenario [43].

In the second scenario, Synthetic Liquid Fuel (SLF) production has been considered to decarbonise the remaining demand of transport fuels. In detail, DME can replace diesel in Internal Combustion Engine Vehicles (ICEVs). More detail about Power-to-Liquid (PtL) production processes considered in the present work have been summarised in Section 3.4.

The Hydrogen scenario envisages the Fuel Cell Electric Vehicle (FCEVs) adoption to convert the remaining conventional vehicles. Thus, the direct use of the hydrogen carrier in vehicles can be applied.

Refuelling stations have been modelled assuming an average capacity of 4000 kg/day and infrastructure costs have been considered according to Ref. [67]. In this scenario, conventional fuel for naval transport has been converted in SLF. Finally, in all scenarios, the demand for jet fuel in air transport has been converted to bio-jet fuel. Assumptions regarding the purchase cost of vehicles is summarised in table Table SM6 of the supplementary material.

In Fig. 4, transport demand in 2019 and in the different 2050 scenarios has been represented.

3.3. *Industry and other sectors*

Much of the industrial demand is normally considered hard-to-abate as it consumes fossil fuels to provide heat at high temperatures.

In Fig. 5, the fuel consumption for each industrial sector in Italy by 2019 has been depicted.

As a first action, it is necessary to identify the potential energy savings that can be achieved in the Italian industrial sector. In so doing, the energy intensity of the industrial sector can be improved. Within the Heat Roadmaps project, a cost curve of energy savings in industry for the Italian energy system has been developed [68]. Accordingly, about 17% of the current demand in industry can be saved in a cost-effective manner. The lifetime for the saving costs in industry has been assumed equal to 20 years [69].

Furthermore, the second step is to electrify space heating and low-temperature process heating. Space heating can be provided by DH and electric HPs. In the analysed scenario, the space heating demand of the industrial sector is divided equally.

Process heating demand below 100 °C can be supplied by HPs. However, it is necessary to consider a large presence of 2-stage HPs to reach the whole temperature range, with a reduction of the average COP.

Nowadays, there is a substantial demand for hydrogen, particularly in the chemical industry, which is supplied by NG through the Steam Methane Reforming (SMR) process. This demand amounts to 0.5 MtH2/yr and can instead be supplied by green hydrogen produced by water electrolysis [70]. The direct use of biomass, which mainly occurs in the wood industry to produce space heating and process heat at low temperatures, is avoided in order to minimise biomass consumption.

Afterwards, two scenarios have been elaborated in order to decarbonise the remaining demand in industry:

- Biofuels
- E-fuels

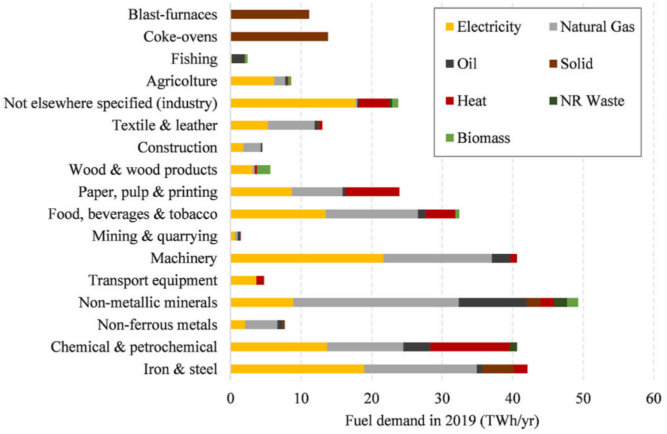


Fig. 5. Fuel consumption for each industrial sector in Italy by 2019.

In the Biofuel scenario, biomethane and bio-liquid fuels have been introduced to replace the fossil fuel demand. In the e-fuel scenario, biomass hydrogenation has been considered to produce (Synthetic Natural Gas) SNG and SLF. Description of Power-to-Gas and Power-to-Liquid production processes has been provided in Section 3.4.

In Fig. 6, current fuel demand in industry and the proposed scenarios by 2050 have been depicted.

3.4. Hydrogen, power-to-Gas and Power-to-liquid

According to Ref. [71], alkaline electrolysers can increase the LHV efficiency up to 70–80% in the long term. An average value of 74% has been considered. The minimum electrolysis capacity varies depending on the scenario. As analysed in Ref. [72], the total electrolyser capacity must be several times higher than the minimum capacity required to meet the annual hydrogen demand. Furthermore, such oversize of electrolyser capacity is crucial in order to provide flexibility to the hydrogen production process and the whole energy system. The same issue concerns the sizing of the hydrogen storage facility. In the present study, an oversized electrolyser power factor of 5 and hydrogen storage of 7 days has been assumed. Hydrogen has been used in the hydrogenation process of both biogas and syngas to produce SNG or SLF. Biogas hydrogenation allows to produce SNG. Furthermore, biomass can be handled according to the gasification process to obtain syngas. Afterwards, syngas hydrogenation allows the synthesis of both SNG and SLF. The operating parameters for the biomass gasification as well as the hydrogenation processes, have been reported in Tables 2 and 3, respectively.

3.5. Flexibility scenarios

Flexibility on the demand side can be created by means different measures. Electricity load can be partially shift by scheduling processes in order to follow RES generation as much as possible. According to Ref. [73], around 15% of electricity demand in the building stock can be shifted in order to provide demand response tools. Furthermore, in Ref. [40] flexible demand equal to around 6% of the electricity demand has been considered to plan a 100% renewable energy system in Europe by 2050. An important share of the flexible demand can also be provided by EVs. Smart charging allows the management of a single power flow direction between the grid and EVs in order to adapt the charging scheduling to RES generation by changing time and power. Furthermore, Vehicle-to-Grid systems can provide temporary electric storage systems by exploiting the electric batteries of EVs.

Two scenarios of flexibility demand have been considered:

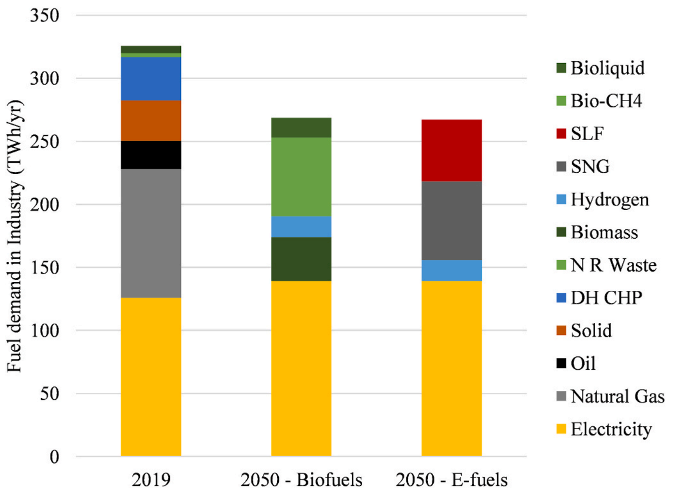


Fig. 6. Fuel demand in industry in 2019 and in the different 2050 scenarios.

Table 2
Biomass gasification plant operating parameters [72].

Parameter	Value
Steam share	0.13
Steam efficiency	1.25
Cold gas efficiency	0.9

Table 3
Operating parameters of hydrogenation processes [72].

Process	Efficiency		Hydrogen share	
	SNG	SLF	SNG	SLF
Biogas hydrogenation	0.83	–	0.50	–
Syngas hydrogenation	0.87	0.60	0.36	0.38

- Low-demand flexibility
- High-demand flexibility

The fist one concerns a share of flexible electricity demand equal to 2 % by means of demand side management. Furthermore, in that scenario 40% of EVs participate to the smart charge scheme, while the remaining part of the EV fleet has a dump charging scheme.

The high flexibility scenario envisages 10% of flexible electricity demand. Moreover, the share of EVs participating in the smart charging scheme is 70% and 10% provide Vehicle-to-Grid services, while the remainder has a dump charging scheme.

3.6. Solar, wind and biomass potential

As pointed out by Ref. [43] one of the main problems in planning 100% renewable systems is the constraint of national biomass potential in order to respect sustainable biomass production chain. According to Ref. [74], the overall biomass potential in Italy is estimated in a range between 170 and 425 TWh/yr, with the average forecasted availability of 250 TWh/yr.

Furthermore, the variable RES (VRES) capacity installation potential represents an important constraint for the analysis and the optimisation problem. Such value for the Italian framework has been assumed according to Ref. [75] and summarised in Table 4.

4. Results and discussion

The optimisation process has led to identify the VRES and EB capacity in the different energy system configurations. In Fig. 7, the results of the optimisation process have been depicted. In detail, RES and lithium-ion battery capacity in the different decarbonisation scenarios has been shown. Furthermore, in Fig. 8, primary energy supply in 2019 and in the different decarbonisation scenarios has been depicted.

Optimisation results are affected by the maximum installable potential of RES. Indeed, in most scenarios the total available capacity of onshore and offshore wind is installed. Only in scenarios where biofuels are used in both industry and transport do these values decrease slightly. The main change between scenarios therefore concerns the installed capacity of PV and EBs. PV capacity varies widely, from around 100 GW to almost 220 GW.

Although Italy has a relatively low wind full load hour and a high

Table 4
VRES capacity installation potential in Italy [75].

RES	Capacity potential (GW)
PV	357.4
Wind onshore	115.4
Wind offshore	55.7

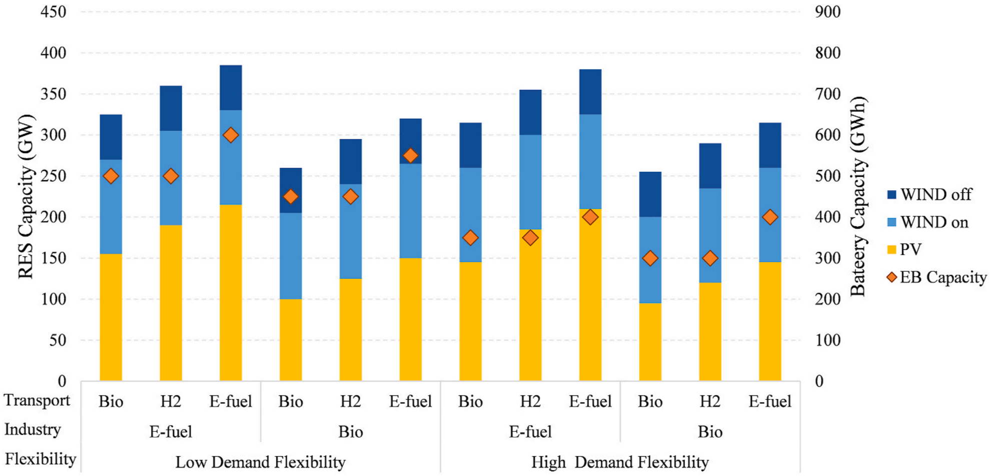


Fig. 7. Results of optimisation process: RES and lithium-ion battery capacity in the different decarbonisation scenarios.

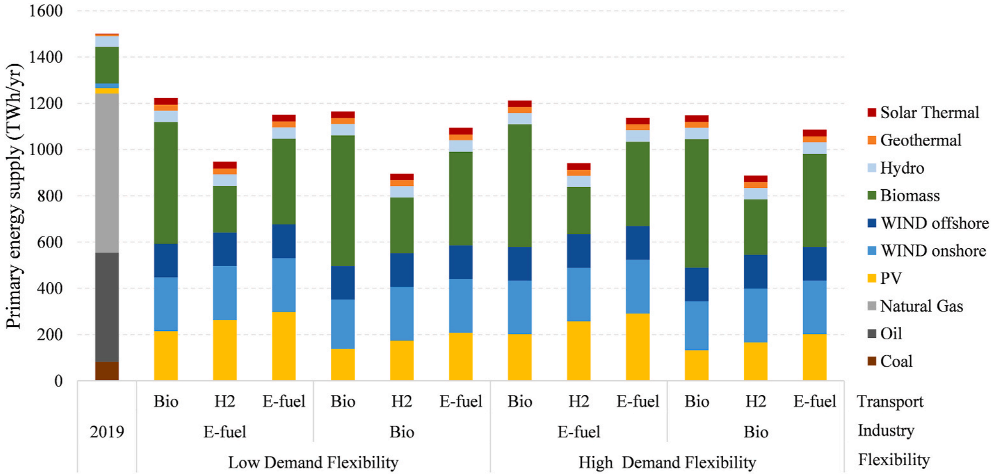


Fig. 8. Primary energy supply in 2019 and in the different decarbonisation scenarios.

photovoltaic full load hour, the optimisation process prioritises the utilisation of the former resource. This is mainly due to the fact that the objective of optimisation is not only economic, but also technical, considering the minimisation of critical excess. Indeed, although PV in Italy is characterised by a very low levelized cost of electricity, wind power has a more distributed annual generation profile, which favours the integration into a 100% renewable system.

The application of biofuels results in a reduction in hydrogen demand and a decrease in the necessity for renewable electricity generation.

The electric storage capacity is subject to the effects of overlapping factors. On the one hand, the additional increase in renewables is almost exclusively from photovoltaics, which results in a highly concentrated critical excess. Consequently, the system requires a substantial increase in storage capacity.

At the same time, the large increase in electrolyser capacity provides the main flexibility option and a form of storage that can integrate the renewable excess. Therefore, the two effects contrast, resulting in a relatively constant capacity of the EBs between the biofuel and hydrogen scenarios.

When transitioning from a biofuel to an e-fuel scenario, there is an increase in stationary storage, but the VRES capacity increases to a greater extent than the overall EB capacity.

Demand-side flexibility has a minimal impact on the installed VRES capacity, resulting in a slight reduction. However, depending on the flexibility scenario, the overall capacity of the EBs varies considerably. Indeed, demand-side management systems enable demand to be adapted to VRES generation, resulting in a reduction in the optimal EB capacity in all scenarios.

In scenarios where direct hydrogen is used in heavy transport, the primary energy supply is lower.

This reduction in the consumption of primary energy can be attributed to the efficiency of FCEVs and in particular, the minimisation of processes associated with the conversion of carriers compared to those employed in the production of electrofuels. In these scenarios, a reduction in primary energy supply of around 200 TWh is observed.

The use of liquid biofuels and biomethane is associated with more primary energy than e-fuels.

The primary energy supply in the decarbonisation scenarios is lower than in the reference scenario. Therefore, the overall system efficiency loss due to storage and carrier conversion systems is less than the efficiency gains due to the elimination of thermoelectric plants fuelled by fossil fuels and the replacement of part of the energy end-users.

Fig. 9 presents a depiction of the annual electricity production, in 2019 and in different future scenarios by 2050. Furthermore, Fig. 10 illustrates the variation in electricity consumption across the different decarbonisation scenarios.

The estimated electricity production in 2050 is more than double that of the current production. Furthermore, the VRES share in electricity production reaches 89%. Biomass, hydro and geothermal energy,

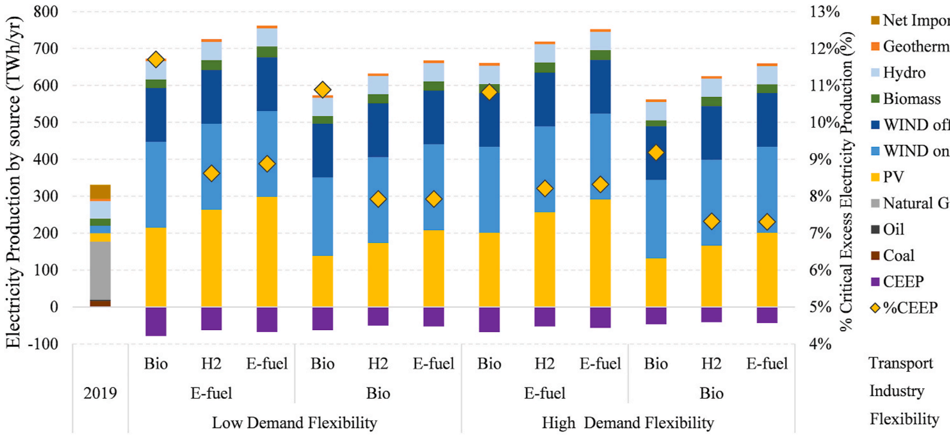


Fig. 9. Annual electricity production in 2019 and in the different decarbonisation scenarios.

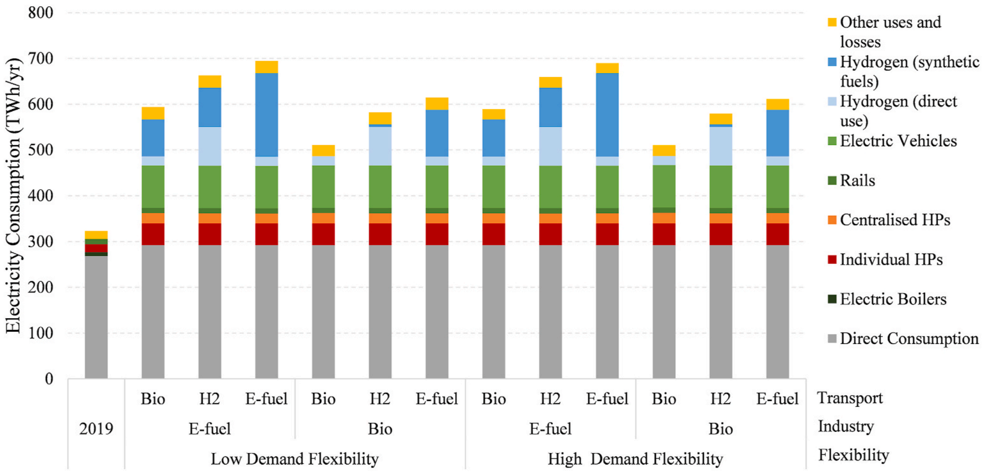


Fig. 10. Electricity consumption in 2019 and in the different decarbonisation scenarios.

along with storage systems, provide sufficient dispatchable generation to balance the energy system during the year.

The CEEP is estimated to range between 7% and 12% depending on the scenario. The increased demand for hydrogen results in a reduction in the critical excess, thereby providing additional flexibility through the power-to-gas strategy. Furthermore, the implementation of high demand-side flexibility measures is also found to reduce CEEP by approximately 2%, depending on the scenario.

Currently, most of the electricity generated is consumed directly. However, in the future, approximately half of it will be converted into other carriers (thermal or hydrogen) or used for other purposes.

In Fig. 11, the hydrogen production versus the VRES share in primary

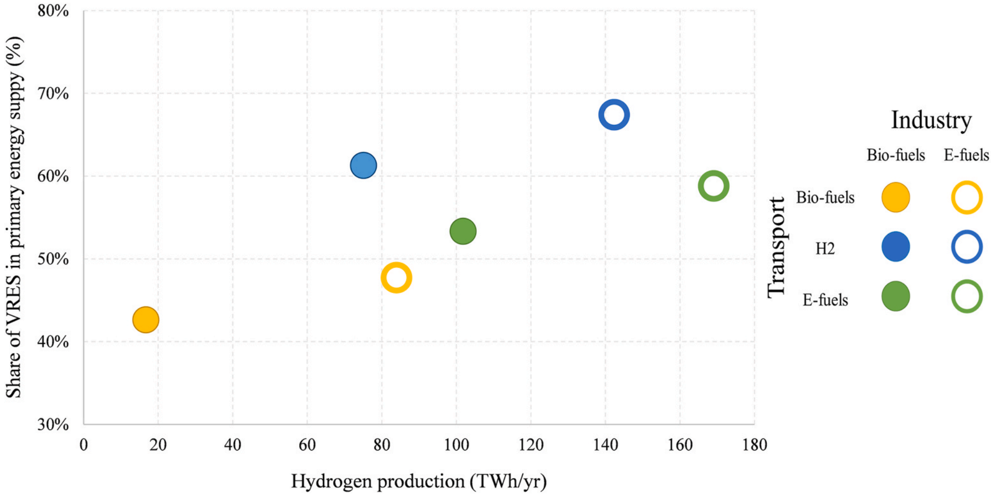


Fig. 11. Hydrogen production versus VRES share in primary energy supply in the different decarbonisation scenarios.

energy supply, in the different decarbonisation scenarios, has been depicted.

The proportion of VRES in the primary energy supply is highly variable and depends mainly on the role of biomass and hydrogen. There is a correlation between the hydrogen production and the penetration of this carrier in end-uses.

The use of e-fuels in transport requires larger quantities of hydrogen than the application of FCEVs, due to the higher efficiency of such vehicles and the efficiencies of e-fuel production processes.

It can be observed that the scenario involving direct hydrogen use in transport allows for an increase in the VRES share against a lower overall hydrogen production.

In the fully biofuels-based scenario, the role of hydrogen is marginal and the VRES share is extremely small. Nevertheless, it is essential to ascertain whether this demand for biomass is consistent with the forecasted availability of this resource in the country under analysis.

The biomass availability is a crucial factor in planning an energy system that considers the sustainability of the biomass production chain. In Fig. 12, biomass consumption in the different decarbonisation scenarios and biomass forecasted availability have been represented.

It is evident that biofuels alone cannot meet the transport fuel demand. Indeed, any scenario that takes that solution into account, far exceeds the biomass availability range. The production chain of e-fuel based on the biomass hydrogenation, also requires a considerable amount of biomass. However, it remains within the range of availability. Only the scenarios involving FCEVs fall below the average biomass availability. Furthermore, it is crucial to highlight that these pivotal biomass production values have been attained despite the minimisation of the biomass role in the electricity generation, building stock and light-duty transport.

Finally, the comparison between the decarbonisation scenarios has been made in terms of the annual costs of the energy system. In Fig. 13, annual costs of the Italian energy system in the different decarbonisation scenarios have been depicted.

The annual costs associated with the direct application of hydrogen in the transport sector indicate a potential limitation. Indeed, this solution is related to higher costs than the application of e-fuels.

The costs of implementing demand-side flexibility, particularly the significant expenditure on smart charging infrastructure, are more than compensated for by the savings made in the EB installation. Furthermore, as previously outlined, this solution also allows for a reduction in CEEP despite the lower electricity storage capacity.

The various strategies exhibit several strengths and weaknesses. With regard to heavy transport, the most energy-efficient solution is the FCEV application. Furthermore, this is the sole strategy that allows biomass consumption to remain below the average availability. However, the costs associated with this scenario are considerably higher than those of the alternative strategies.

The use of biofuels alone is not a viable solution, as they exceed the availability range. However, the process of hydrogenating biomass to produce SLFs for transport is promising. Indeed, that solution allows costs to be reduced compared to other scenarios, despite the higher VRES capacity. The use of biofuels in industry is associated with a slight reduction in costs compared to the electro-fuel application. However, the combination of biofuels in industry with SLFs in transport results in a biomass level that is very close to the maximum potential available.

The high demand-side flexibility scenario has advantages in its application, both in terms of energy and economics. Therefore, that solution is a strategy to be implemented as far as possible.

4.1. *Discussion, limitations of the work and further developments*

The results of this work show that a 100% renewable energy system in Italy is technically and economically feasible.

Furthermore, some consideration about the energy planning process can be made. As well as energy systems must move towards integration between sectors, energy planning cannot evaluate one sector at a time, but all strategies must be investigated by analysing synergies and influences on the whole system. Therefore, the combined simulation of different measures within the national energy system is crucial for the appropriate assessment of their impact, especially when the analysis includes both renewable power plant installations and sector coupling measures.

In this paper, the optimisation process is limited to the definition of renewable and stationary electrochemical storage capacities. However, this energy system design approach makes it possible to describe the differences between the different energy demand scenarios elaborated in this paper.

This methodology allows the optimisation of certain variables to be integrated into a simulation approach in which alternative scenarios are compared and their impact on the energy system is analysed.

The proposed approach therefore differs from other optimisation tools such as EPLANopt, which integrates EnergyPLAN with a multi-objective evolutionary algorithm (MOEA) that minimises annual costs and CO$_2$ [76]emissions by optimising several decision variables [76]. In addition, that tool has been more widely applied to optimise energy system configurations during the transition phase than 100 % renewable energy system configurations.

In contrast, the proposed approach minimises annual costs and CEEP by focusing exclusively on 100 % renewable systems.

Other works, such as Ref. [77], coupled EnergyPLAN with a grey wolf optimisation algorithm using MATLAB in order to define the

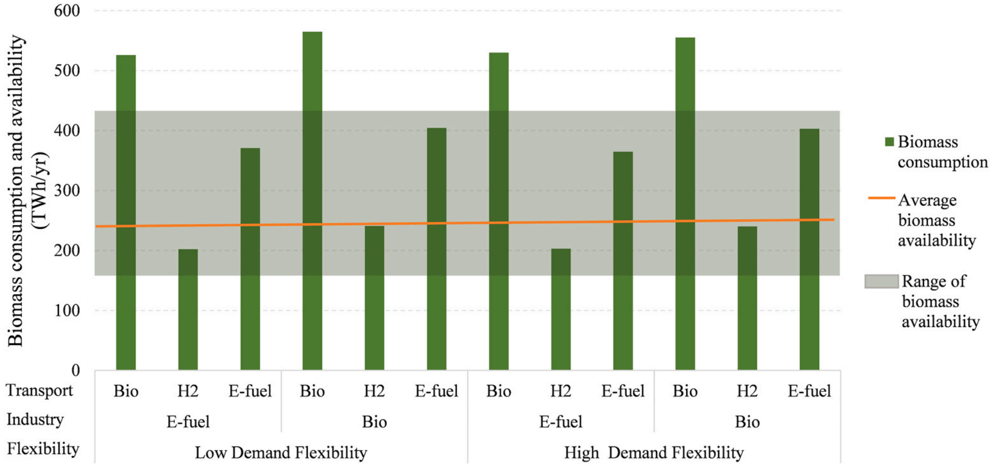


Fig. 12. Biomass consumption in the different decarbonisation scenarios and biomass forecasted availability.

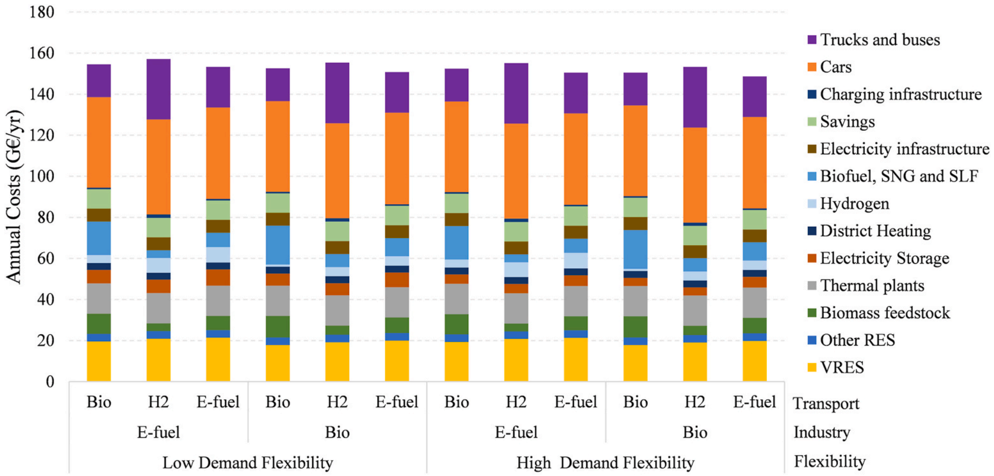


Fig. 13. Annual costs of the Italian energy system in the different decarbonisation scenarios.

capacity of the technologies in the proposed scenario. In that study, optimisation is performed with the single objective of minimising energy system costs.

Furthermore, this work uses EnergyPLAN as a static model and does not integrate long-term optimisation of the energy system. For example, EPLANoptTP proposes an algorithm that exploits the features of EnergyPLAN in a long-term optimisation system with a perfect foresight approach, which tends to minimise both costs and cumulative emissions over the period [78].

Moreover, the approach presented is limited to the optimisation of a few variables, and future developments of this work could include additional variables into the optimisation process. The use of different computational tools integrating different objective functions, as well as the comparison of the configuration of an Italian 100% renewable energy system identified by means of different static and long-term optimisation tools could be topics for future developments of this work.

5. Conclusions

The aim of this paper is to analyse various configurations to achieve a 100% renewable energy system in Italy by 2050, with a particular focus on strategies for the decarbonisation of hard-to-abate sectors. A comprehensive investigation is undertaken to assess the potential for decarbonising all energy sectors within a single model. The focus is on the interrelationships and broader implications of the collective adoption of various alternative solutions.

The main outcomes can be summarised as follows:

- This study demonstrates the technical and economic feasibility of a 100% renewable energy system in Italy. Power-to-X technologies will play a key role in future decarbonised systems to balance intermittent generation, minimise the need for large stationary electrical storage capacity and reduce biomass consumption.
- Energy savings in the building stock and in industry are essential to reduce final energy demand.
- The electrification of heat demand and light transport is essential to increase the penetration of renewable electricity in energy end-uses and to provide system flexibility measures. In addition, the deployment of DH can efficiently and cost-effectively meet a large share of the heat demand in buildings.
- The maximum installable potential of RES has a significant influence on the results, with wind power being prioritised over PV due to its more distributed annual generation profile. This is despite Italy having a high number of PV full load hours and consequently a low levelized cost of electricity. This priority is driven by the necessity to minimise critical excesses and ensure system stability in a 100% renewable energy system.
- The biomass availability emerges as a crucial factor in energy system planning. The results demonstrate how various scenarios exceed or align with the biomass availability range. This underscores the importance of considering biomass constraints when formulating decarbonisation strategies.
- Regarding heavy transport, the FCEV application allows for the greatest reduction in primary energy supply. This reduction can be attributed to the efficiency of FCEVs and the avoidance of processes for producing electrofuels. Furthermore, this is the only strategy that keeps biomass consumption below average availability. However, the costs associated with this scenario are considerably higher than those of alternative strategies.
- It is not feasible to rely solely on biofuels for decarbonisation, as the use of biofuels exceeds the available resources. However, the biomass hydrogenation to produce SLFs is promising and offers a cost reduction despite the increased VRES capacity. While the use of biofuels in industry slightly reduces costs compared to electrofuels, the combination of biofuels in industry and SLFs for transport brings biomass consumption very close to its maximum potential. Synergies between bio-based fuels and electrofuels should be exploited to optimise the different value chains.
- A highly flexible demand-side approach has both energy and economic advantages. This strategy should therefore be a priority wherever possible.

In conclusion, the analysis of hard-to-abate sectors is crucial for planning 100% renewable energy systems. Just as energy systems must move towards integration between sectors, energy planning cannot evaluate one sector at a time. All strategies must be examined by analysing synergies and influences on the whole system. Indeed, the whole configuration of the energy system is affected by strategies to decarbonise heavy duty transport and industrial heating demand.

Therefore, the combined simulation of different measures within the national energy system is crucial for a proper assessment of their impact.

Finally, the path to a 100% renewable energy Italy faces several technical and economic challenges. In this framework, the present article contributes to the scientific and political debate by showing that a complete decarbonisation based only on domestic renewables is possible.

Nomenclature

(continued on next page)

(*continued*)

CEEP	Critical excess electricity production
CEEP	Critical excess electricity production
DH	District heating
DME	Dimethyl ether
EB	Electric Battery
EV	Electric vehicles
FCEVs	Fuel Cell Electric Vehicle
ICEVs	Internal Combustion Engine Vehicles
MAT4EnergyPLAN	MATLAB Toolbox for EnergyPLAN
PV	Photovoltaic
PtL	Power-to-Liquid
RES	Renewable energy sources
SLF	Synthetic Liquid Fuel
UP	Utopia Point
VRES	Variable RES

CRediT authorship contribution statement

Lorenzo Mario Pastore: Writing – original draft, Software, Investigation, Data curation, Conceptualization. **Livio de Santoli:** Supervision.

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.energy.2025.134749.

Data availability

Data will be made available on request.

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