

## Decarbonising Italy's energy system with high-resolution thermal demand: Insights from a TRNSYS–H2RES integrated model

Francesco Calise<sup>a</sup>, Francesco L. Cappiello<sup>a</sup>, Luca Cimmino<sup>a,\*</sup>, Neven Duic<sup>b,c</sup>, Antun Pfeifer<sup>b</sup>, Francesca Pugliese<sup>d</sup>, Maria Vicidomini<sup>a</sup>

<sup>a</sup> Department of Industrial Engineering, University of Naples Federico II, Naples, Italy

<sup>b</sup> Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Zagreb, Croatia

<sup>c</sup> Pontificia Universidad Católica de Valparaíso, Valparaíso, Chile

<sup>d</sup> GRASTIM JV, Via Nuova Marina 5, Naples, 80133, Italy

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### ABSTRACT

Energy planning is essential for analyzing future energy scenarios, yet it remains a complex and data-intensive process, particularly in modeling thermal demand. Simulation tools like TRNSYS provide a robust approach for generating realistic thermal demand projections, which are critical for accurate scenario analysis. This study highlights that achieving decarbonization goals requires electrification, particularly in heating and transport, as electricity-based technologies significantly reduce emissions. However, this transition necessitates substantial investments in renewable energy, with solar photovoltaic and wind power becoming dominant. The H2RES model aligns with Italy's Long-Term Energy Strategy, projecting that electricity generation must reach 600–700 TWh by 2050, with renewables supplying nearly 100% of demand. A major challenge is managing the variability of solar and wind power to prevent curtailment using flexibility options. Power-to-X technologies, particularly Power-to-Heat, are explored as solutions, with TRNSYS simulations emphasizing the efficiency of heat pumps over conventional heating systems. Full electrification of heating could require an additional 100 GW of heat pump capacity, though integrating biomass could reduce this by 30%. Offshore wind is crucial for winter heating demand. Key challenges include bureaucratic barriers, the pace of renewable expansion, and the development of energy-balancing technologies to ensure a successful transition.

### 1. Introduction

The EU targets for 2050 include the energy transition from energy systems based on dispatchable, centralized, fossil-fuelled generation, to distributed, variable renewable energy-based generation and smart, responsive demand in integrated energy systems of the future [1,2].

In the scientific literature, most studies are focusing on the electricity sector, while increasing number of studies also consider heating, cooling, industry, and transportation as part of the overall energy system [3, 4]. These two perspectives are commonly used in literature reviews regarding industrial energy reduction, alternative fuels, and strategies for CO<sub>2</sub> emissions reduction [5]. Increasing interest in 100% Variable Renewable Energy Sources (VRES) electricity integration into the integrated energy systems is evident among stakeholders [6], with countries like Sweden, California, and Norway targeting full VRES integration by 2045 or 2050 [7]. Similarly, cities such as Copenhagen, Frankfurt, and

Vancouver aim to transition to 100% VRES grids by 2050. Major corporations, including Walmart, BMW, and IKEA, alongside technology giants like Sony, Google, Facebook, Apple, and eBay, are committing to similar goals [8]. Even Wartsila, traditionally a fossil energy company, has pledged to achieve 100% VRES by 2050 [9]. Broader regional efforts include initiatives in North Africa, Europe, and Australia [10].

Expanding renewable energy integration requires advanced modeling tools to optimize energy systems across electricity, heating, and storage sectors [11]. In this context, the concept of smart energy systems has gained increasing relevance as a holistic framework for analysing deep decarbonization pathways by jointly considering electricity, heating, cooling, transport and fuel sectors, together with storage and sector coupling options. Unlike smart grid approaches focused primarily on electricity networks, smart energy systems explicitly address cross-sectoral interactions and flexibility, highlighting the central role of heating electrification and thermal demand management in

\* Corresponding author.

E-mail address: [luca.cimmino@unina.it](mailto:luca.cimmino@unina.it) (L. Cimmino).

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high-renewable systems [12,13]. Previous studies have shown that renewable heating strategies significantly affect storage needs, grid operation and the balance between electric and thermal flexibility, underlining the importance of integrated modelling approaches for long-term energy planning.

Indeed, the development of novel tools for increased accuracy in renewable energy generation is becoming increasingly appealing for researchers [14]. A GIS-based study for Italy shows that a 100% renewable power system using a hybrid PV-wind setup requires significant storage capacity, with pumped-hydro emerging as the most cost-effective solution [15]. Furthermore, specific attention is paid to remote areas where hybrid renewable systems can provide reliable cost-effective solution to decarbonization [16]. Similarly, integrating district heating into European energy models highlights cost advantages when utilizing excess industrial heat and large-scale heat pumps [17]. Operational planning for district heating systems further benefits from non-linear modelling approaches, enhancing efficiency and reducing costs [18]. Smart energy systems can be optimized using deep reinforcement learning, which improves real-time decision-making in district heating and cooling networks [19]. Seasonal thermal energy storage has also been identified as a key solution for decarbonizing district heating, particularly in regions with high winter heat demand [20]. Electricity storage requirements in Austria emphasize the need for long-duration storage, such as hydrogen, to maintain system stability under high shares of wind and solar power [21]. Electric batteries present several concerns but lot of research is being conducted, as ImpFilm cooling, to bypass them and provide efficient electricity storage [22]. However, hydrogen is stealing the spotlight for the versatility of options for both production and storage [23]. Optimized district heating networks integrating multiple energy sources further reinforce the importance of strategic planning in decarbonizing urban heating supply [18].

In Southeast Europe, national energy systems have been modelled under the assumption of perfect transmission between zones using EnergyPLAN [24], proving useful for simpler systems without dispatchable fossil-fuelled generators [25]. However, to assess strategic decisions in interconnected energy markets, tools capable of cross-border transmission modeling and unit commitment optimization are required [26]. Dispa-SET has been employed for such purposes, analysing the role of centralized cogeneration plants with thermal storage [27], optimizing interconnected energy systems with high VRES penetration, verified in comparison to the commercial tools [31], providing comprehensive modelling capabilities to evaluate integrated energy solutions, used in analysis of different demand response approaches as well [32,33]. Also, H2RES has been used already for the analysis of decarbonization of district heating sector of Italy in Ref. [34], providing the measures for decarbonization of the building stock, but soft-linking with TRNSYS has not been explored.

Recent modelling studies of the Italian energy transition consistently showed that deep decarbonization pathways relied on large-scale deployment of variable renewable energy sources, strong electrification of end-use sectors and enhanced system flexibility, regardless of the modelling framework adopted [35,36]. Whole-energy-system analyses based on EnergyPLAN indicated that meeting Fit-for-55 and long-term climate targets required a rapid shift from fuel-based residential heating technologies toward electric heat pumps supplied by renewable electricity [36]. Similar conclusions were obtained using the H2RES optimization model, where biomass progressively lost competitiveness in residential heating as electrification and sector coupling expanded

under net-zero scenarios [37]. Studies employing the EnergyScope framework further demonstrated that limited sustainable biomass availability constituted a binding constraint, leading to its optimal allocation toward industrial processes and dispatchable power generation rather than widespread residential heat supply [35]. Long-term capacity-expansion analyses using TEMOA-Italy confirmed that, even under unfavourable financing conditions for capital-intensive technologies, electrified heating solutions remained system-optimal compared to biomass-based residential options [38,39]. Power-sector-focused modelling with OSeMOSYS showed that high-VRES systems combined with storage and hydrogen flexibility reduced electricity system costs and indirectly accelerated the electrification of residential heat, further eroding the role of biomass in this sector [40]. When energy-system models were soft-linked with macroeconomic frameworks, TIMES-RSE-based assessments revealed that residential biomass heating delivered limited economy-wide benefits once externalities, health impacts and resource competition were internalised [41]. Analyses integrating circular-economy strategies concluded that biomass was more effectively exploited through cascading use of residues or waste-to-energy pathways rather than through direct combustion in residential heating systems [42].

Compared to this body of literature, the present study contributes by explicitly coupling dynamic building-level simulations with a national energy system optimization model. The integration of TRNSYS-generated, hourly heating and cooling demand profiles—resolved by building typology and climatic zone—into H2RES allows a more precise assessment of the competition between biomass-based heating and heat pump electrification, capturing both demand-side efficiency effects and system-level constraints. This modelling approach reduces reliance on stylised load assumptions and provides a more robust evaluation of residential heating decarbonization pathways under Italian conditions.

While the reviewed studies converge on similar long-term decarbonization outcomes, they differ substantially in how residential heating demand is represented. Most national-scale analyses for Italy rely on aggregated or stylised demand profiles, exogenous efficiency improvements, or static representations of the building stock, without explicitly modelling the hourly dynamics of heating and cooling demand across climatic zones. In contrast, the present study integrates dynamic, building-level thermal simulations generated in TRNSYS into the H2RES optimization framework, allowing demand-side efficiency, electrification, and system constraints to interact endogenously over time. This distinction is particularly relevant for assessing the competition between biomass-based heating and heat pump electrification, as well as the implications for peak loads, renewable integration, and system flexibility.

### 1.1. Aim and novelty of the study

This study aims to develop a dynamic modeling approach for energy demand analysis in energy system planning for Italy's transition to a sustainable, carbon-neutral energy system by 2050. The research integrates a dynamic simulation model for residential heating and cooling demand with the H2RES energy planning optimization tool to: i) optimize the Italian energy mix from 2020 to 2050 under different transition scenarios; ii) improve energy system modeling accuracy by incorporating dynamic demand profiles rather than static assumptions; iii) evaluate the impact of key transition policies, such as full electrification of heating, renewable energy expansion, and biomass restrictions, on emissions and system flexibility. By simulating multiple scenarios, the study provides critical insights for policymakers and stakeholders in shaping Italy's long-term energy strategy.

Unlike conventional energy planning studies that rely on static demand assumptions, this research dynamically models heating and cooling demand using TRNSYS software [43]. The approach includes a graphical modeling of typical Italian residential buildings in Google SketchUp and dynamic thermal simulations in TRNSYS 18 to calculate

heating and cooling demand under varying climatic conditions [44]. Real environmental factors (temperature, humidity, solar radiation) and building characteristics (insulation, window glazing, heat gains) are therefore considered in the simulation and the validation against real consumption data from Odyssee-Mure is provided to ensure accuracy.

These detailed hourly demand profiles were then integrated into H2RES, ensuring a more realistic representation of the energy system needs over time. With this methodology, this study bridges the gap between realistic thermal demand forecasting and energy system optimization, providing a high-resolution demand profile for better scenario analysis. Additionally, three different energy transition scenarios are analyzed, highlighting the role of biomass restrictions, complete electrification of heating, and renewable energy expansion in shaping the future energy mix.

The findings provide strategic recommendations on investments in renewables (solar, wind, and hydrogen), energy storage, and electrification to achieve Italy's decarbonization targets. This study sets a new standard in energy planning by integrating realistic, dynamic demand simulations with long-term strategic optimization, offering a more precise and policy-relevant framework for achieving a sustainable and carbon-neutral energy system. The key novelties can be summarized as follows:

- Advanced modeling of residential heating and cooling demand using TABULA analysis, clustering Italian residential buildings and simulating environmental conditions across different climatic regions.
- System-level analyses embedding high-resolution, climate- and typology-specific residential demand profiles derived from TRNSYS into the H2RES optimization framework. This allows a more realistic assessment of the interaction between building-level efficiency, electrification of heating, and biomass constraints at the national scale.
- Comprehensive energy transition assessment through the evaluation of multiple transition scenarios, integrating biomass restrictions, full electrification of heating, and renewable energy expansion, while exploring Power-to-X (PTX) technologies like heat pumps and hydrogen storage to enhance system flexibility.

## 2. Material and methods

This research developed a novel energy planning approach based on the integration of dynamic simulation model for the thermal energy demands for heating and cooling in the residential sector within an energy planning optimization algorithm. For dynamic simulation of residential sector demand, TRNSYS software was used, which is widely adopted and recognized as a milestone for energy system dynamic simulation [45]. The energy planning optimization platform is H2RES, an open-source software developed to model and optimize the long-term configuration of energy systems [32]. The software handles hourly data series for demand, storage, and supply across water, electricity, heat, and hydrogen. The tool features modules that support modeling of renewable energy sources, desalination processes, battery storage, grid connections, and fossil fuel integration. The economic optimization performed, based on the minimization of operating costs, considers the CEEP limits (Critical Excess of Electricity Production) [46], RES penetration and yearly limits on CO<sub>2</sub> emissions levels. The model has been implemented to consider the constraint on biomass consumption too.

In the present work, H2RES software has been applied to model the transition of the Italian energy system, identifying the optimal energy mix with a 5-year step from 2020 to the horizon year of 2050. Since years 2020 and 2021 are affected by the COVID-19 pandemic and the data are not representative of the real energy consumption, 2019 has been considered as the reference year. The input energy dynamic demand profiles, together with the fuels prices, import/export data, and technologies availability, are provided to the optimization algorithm as csv files. Table 1 summarizes all these inputs and the databases from

**Table 1**  
Data sources for the collection of the model input.

Input data	Source
Electricity demand	Terna
Industrial/commercial heating demand	Odyssee Mure
Industrial/commercial cooling demand	Odyssee Mure
Hydrogen demand	TERNA, IEA
Fuel prices	AIEL, TERNA, MATTM, ARERA
Import and export	TERNA
Electric transport demand	EUROSTAT, SISTAN
Availability factor of dispatchable power plants	TERNA
Inflows data	TERNA
Genco (characteristic data of the Italian power plants divided into dispatchable units – DU - and non-dispatchable units – NDU)	GSE, TERNA, SNAM, MASE
FLEX TECH (all data referred to technologies used to produce district heating and individual heating - including domestic hot water - and power to heat technologies).	ASSOCLIMA, ENEL, IEA

which the information are collected.

Fuel prices for fossil energy carriers were assumed constant over the modelling horizon and based on 2019 reference values. This choice was made to focus on structural system effects driven by electrification, renewable integration, and policy constraints, rather than on uncertain future price trajectories. Similar assumptions have been adopted in recent long-term energy system studies, where fossil price sensitivities were shown to mainly affect total system costs without altering optimal technology configurations [47].

For residential heating and cooling demands, a different analysis was necessary, due to the lack of these data in the literature and the difficulty in evaluating an hourly request that could be placed as input in H2RES. Therefore, to model these dynamic data, a dynamic simulation model for typical buildings in Italy was developed, starting from a geometrical modelling of Italian buildings with Google SketchUp and a dynamic simulation of these buildings with the TRNSYS software. The selection of the building types, constructive features, and climate zones was based on a statistical analysis whose details are provided in the *Model* section.

The results obtained from the dynamic simulation were used in H2RES and allowed to simulate the Italian energy system in 2019 and future energy scenarios under different hypotheses of intervention in the residential thermal sector and with different technologies used in it.

## 3. Model

This section discusses the modeling of the dynamic heating and cooling demand profiles in TRNSYS and the optimization set up in H2RES.

### 3.1. H2RES model

H2RES is an optimization model based on Linear Programming, able to provide a long-term capacity investment and dispatching optimization. H2RES allows to plan an energy system over short-to-long horizons, optimizing capacity additions for technologies with hourly scale resolutions for energy dispatch [9]. By using H2RES it is possible to minimize annual costs and identify optimal capacity investments for different technologies. The model takes into account various costs like operating costs, capacity investment, fuel costs, CO<sub>2</sub> emissions:

$$\sum_y \sum_p \sum_t df_y \left[ vC_{t,p,y} D_{t,p,y} + C_{t,y} K_t Inv_{t,y} + R_{t,p,y} Ramp_{t,p,y} + I_{p,y} Imp_{p,y} + CO_2 Price_y CO_2 Levels_{t,p,y} \right]$$

The first term corresponds to the variable cost for dispatching a technology (t), in each period or hour (p), and for each year (y), the second term represents the cost incurred per unit of additional capacity

of a given technology (e.g. €/MW), the third term represents the increase and decrease in costs, the fourth term represents import costs and the last term represents the cost per unit of CO<sub>2</sub> emission for each technology.

Four main categories of constraints are used in the H2RES optimization:

- 1. Dispatching and technical constraints:** generators and energy storage systems are constrained by their maximum operating capacity, minimum operating capacity, availability factors (dispatchable and non-dispatchable power plants). The total available capacities are changed from year to year as the total capacity that change if there are investments in new capacity and decommissioning.
- 2. Storage constraints:** the storage level is modelled on an hourly basis for each year. Each storage unit has a minimum and maximum state of charge that must be guaranteed for each hour of the time horizon. H2RES considers technologies with determined capacities (stationary electric batteries and EV batteries) and others with variable (optimized) storage capacity, such as hydrogen and heat storage (heat pumps and electric boilers).
- 3. Demand constraints:** this set of constraints ensures that the demand for electricity, heat, transport and hydrogen, in industry and other sectors, is met at every hour and year in the time horizon.
- 4. Policy constraints:** H2RES considers the level of critical excess electricity production (CEEP) allowed during a given year, the share of renewable energy and the level of annual CO<sub>2</sub> emissions. These constrains can be turned on or off depending on the type of scenario set as target.

The model can integrate a wide range of technologies, spanning from conventional power generators to renewable energy sources such as solar, wind and hydro-river (HROR) systems. The power and heating sectors are interconnected through technologies like Electric Boilers (EBs), Heat Pumps (HPs), and Combined Heat and Power (CHP) plants. Additionally, conventional boilers can also meet heating demands. In the H2RES framework, multiple technologies are grouped under the same category as EBs or HPs but differ in technical parameters, capacities, and costs (e.g., air-to-air, air-to-water, or ground source heat pump). These technologies can be used as Power-to-Heat (PtH) solutions, offering significant flexibility due to their storage capabilities.

For instance, cogeneration plants produce both electricity and heat

from natural gas. If this natural gas is replaced with green fuels, the system can transition into Power-to-X (PtX) applications. Electric heating can generate low-temperature heat via heat pumps or high-temperature heat through electric boilers. This heat can be used immediately or stored to absorb excess energy from non-dispatchable sources, preventing waste.

Fig. 1 illustrates the relationships between different energy generation technologies, flexibility options, secondary transformation sectors, and final demand sectors.

### 3.2. TRNSYS model

TRNSYS is a widely adopted software both for commercial and academic purpose used to simulate the behaviour of transient systems [49]. The modular nature of the software makes it very flexible thanks to the possibility of adding mathematical models that are not present in the standard library and obtaining extremely accurate simulations [50]. In the following study, TRNSYS18 was used to carry out a dynamic simulation of the most common buildings in Italy and calculate the residential heating and cooling demand. With this approach, it was possible to simulate different buildings behavior under variable weather conditions, all across the country [51].

The space heating energy demand of the building is dynamically calculated using Type 56 of TRNSYS, in conjunction with the Google SketchUp TRNSYS3d plug-in to integrate the building 3D geometry [52]. Simulations are performed on various types of building representative of Italian construction. The model accounts for the impact of environmental conditions (temperature, humidity, solar radiation, etc.), envelope thermophysical properties, and internal heat gains. Each thermal zone corresponds to a single room, ensuring an accurate simulation of the control system, where each room has its own radiator and thermostat. Type 56 includes a moisture balance model that considers sorption effects by increasing the air's effective moisture capacity. The moisture balance equation for any air node is:

$$M_{eff,i} \frac{dx_i}{dt} = \dot{m}_{inf,i}(x_a - x_i) + \sum_k \dot{m}_{vent,k,i}(x_{vent,k} - x_i) + W_{g,i} + \sum_j \dot{m}_{cpl,g,s}(x_j - x_i) \quad (1)$$

Where  $x_i$  is the humidity ratio of the air node,  $x_a$  is the ambient humidity ratio,  $x_{vent,k,i}$  is the ventilation air humidity ratio,  $M_{eff,i}$  is the effective moisture capacitance,  $W_{g,i}$  represents internal moisture gains,  $x_j$  is the

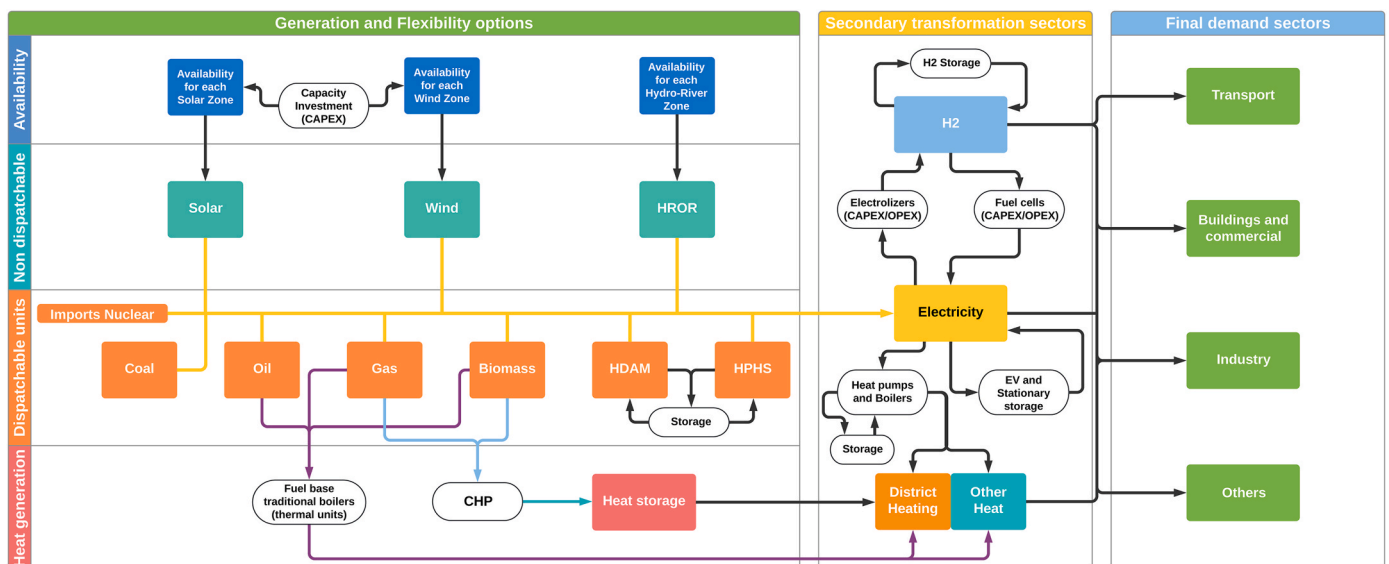


Fig. 1. Integrated energy system model in H2RES: pathways for power, heat, and hydrogen transformation [48].

humidity ratio of adjacent air nodes.

The thermal balance for the air node in a thermal zone is given by:

$$\dot{Q}_i = \dot{Q}_{surf,i} + \dot{Q}_{inf,i} + \dot{Q}_{vent,i} + \dot{Q}_{cplg,i} + \dot{Q}_{cg,i} + \dot{Q}_{solar,i} + \dot{Q}_{ISHCCL,i} \quad (2)$$

Where  $Q_{surf,i}$  is the convective gain from surfaces,  $Q_{inf,i}$  and  $Q_{vent,i}$  are infiltration and ventilation gains,  $Q_{cplg,i}$  represents gains due to air exchange between nodes,  $Q_{cg,i}$  accounts for internal convective gains,  $Q_{solar,i}$  is the solar radiation fraction entering through windows,  $Q_{ISHCCL,i}$  represents absorbed solar radiation by internal shading devices.

Walls are modelled using the transfer function method of Arsenault and Mitalas, considering heat transfer from surface to surface [53]. Windows are simulated using data from WINDOW 4.1 (Lawrence Berkeley Laboratory), accounting for absorption, transmission, and reflection of solar radiation for up to six-pane glazing systems [54]. Long-wave radiation exchange between surfaces is modelled using the Gebhart Method, which is particularly useful for low-emissivity (low-e) materials and detailed thermal comfort analysis [55].

#### 4. Case study

This section discusses the data collection for creating the Italian energy profile and trend for the forthcoming years, and the modelling of the individual residential heating and cooling demands in TRNSYS.

##### 4.1. Data collection for modelling H2RES scenario

The Italian case study involved modelling future scenarios based on real data extracted from scientific literature and official database. From the data reported by TERNA [56], it was possible to obtain the total electricity demand value for 2019, equal to 319,674.4 GWh, as shown in Fig. 2, as well as its hourly distribution for the same year, see Fig. 3. To estimate the energy consumption for the forthcoming years, the same distribution was considered, due to the lack of predictive models for the energy consumption trends. However, H2RES adjusts the load profile to meet the constraints imposed during the setup phase. Data regarding energy imports and exports were also obtained from TERNA.

In line with common practice in long-term energy-system modelling, the hourly electricity demand profile is assumed to remain constant in shape and scaled over time according to projected electricity consumption. Previous studies have shown that while different demand patterns can affect flexibility requirements and peak loads, their influence on system cost and generation mix is generally limited compared to uncertainties on technology costs and policy assumptions [57]. Given the large uncertainty associated with future electrification-driven demand behaviours, a historical pre-pandemic profile (2019) is adopted as a neutral baseline, while the evolution of total electricity demand

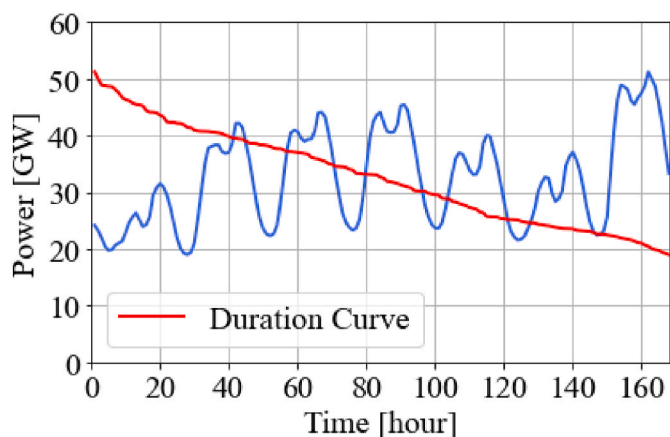


Fig. 3. Electricity demand (first week of 2019).

follows the PNIEC trajectory [58,59]. Fig. 4 illustrates the resulting electricity demand profiles for selected years (2020, 2030, and 2050), highlighting that demand growth is captured through scaling of a consistent hourly shape.

The hydrogen demand for 2020 is assumed to be zero because it refers exclusively to green hydrogen, which is not yet in use. Currently, hydrogen production in Italy is almost entirely grey, derived from natural gas through steam reforming [60], and primarily used in industrial applications such as ammonia synthesis for fertilizers, oil refining, and methanol production [61]. Since H2RES considers only green hydrogen for energy production, a value of zero is assigned for the reference year. For subsequent years, projections from TERNA and the IEA (International Energy Agency) on the evolution of total hydrogen demand in Italy are considered (see Fig. 5).

The variability of fuel prices is a crucial factor in the economic analysis conducted by H2RES. Table 2 shows the annual average prices considered for different fuels, including biomass [62], coal [56], diesel [63], oil [64], and gas [64]. These prices reflect market conditions for the reference year and were assumed constant for the subsequent years analyzed in this study. Renewable energy sources, in contrast, are considered to have zero cost. The inclusion of these values allows for a more accurate assessment of the economic feasibility of hydrogen production and integration within the energy system.

The H2RES model integrates the transport sector by considering electric vehicles (EVs) not only as consumers but also as flexible energy storage assets. This is achieved through the incorporation of smart charging and vehicle-to-grid (V2G) strategies, enabling bidirectional power flow to support grid stability. Key parameters analyzed include

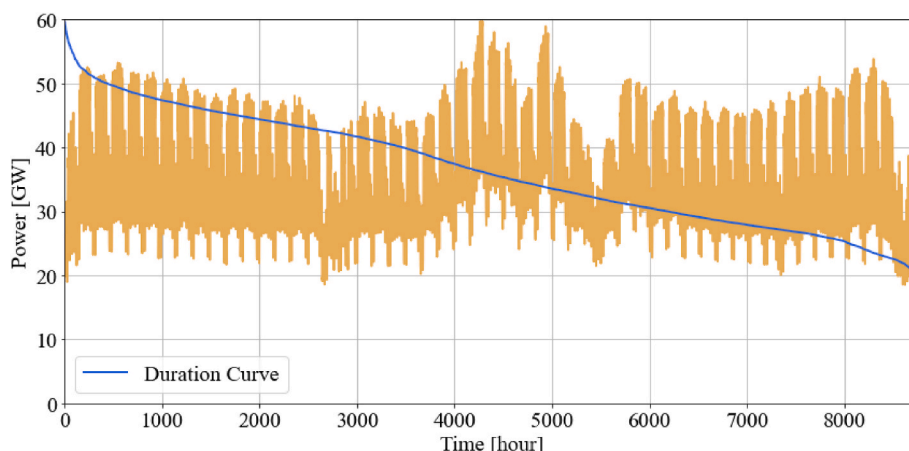


Fig. 2. Electricity demand for the whole year 2019.

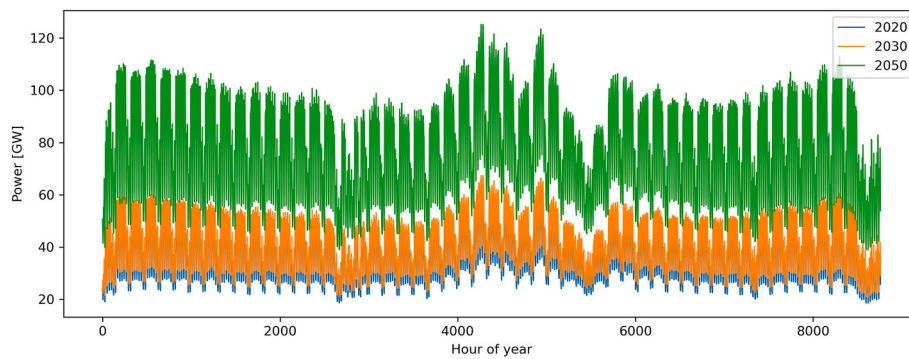


Fig. 4. Increase of electricity demand over years (2020-2030-2050).

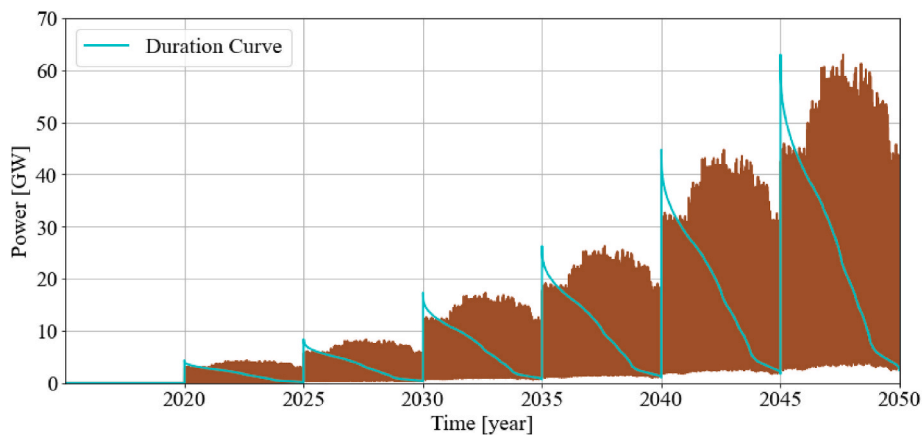


Fig. 5. Annual hydrogen demand trend from 2019 to 2050 in GWh.

Table 2

Annual average reference fuel prices adopted in the model. Fossil fuel prices are based on European reference values from the EU Reference Scenario and IEA World Energy Outlook, while biomass prices reflect typical cost ranges used in EU energy-system studies [71,72].

Fuel	Value	Unit
Biomass	26	€/MWh
Coal	7.16	€/MWh
Diesel	138.13	€/MWh
Oil	64.22	€/MWh
Gas	16.06	€/MWh

Table 3

Electricity generation and installed capacity of renewable sources in Italy in 2019. Data derived from national electricity statistics reported by Terna and GSE [56].

Technology	Production [TWh]	Capacity [GW]
Hydro	46.3	19
Wind	20.2	10.7
Photovoltaic	23.7	20.9
Geothermal	6.1	0.8
Bioenergy	19.6	4.1
Total	115.9	55.5

V2G pricing mechanisms, fleet size, electricity demand, battery specifications, and connection availability. A long-term electrification scenario is assumed, targeting 50% electrification of the transport sector by 2050, with 7 kW charging/discharging power per vehicle and an average battery capacity of 50 kWh per EV [65].

As of 2019, renewable energy sources accounted for 36% of Italy electricity demand, with hydropower being the dominant source [66]. H2RES incorporates detailed renewable generation data by categorizing energy sources into: i) non-dispatchable renewables, including solar PV, wind, and run-of-river hydropower, which exhibit variable generation profiles; ii) dispatchable renewables, primarily hydropower with storage, which can be managed to meet demand fluctuations. Other renewable sources such as geothermal and biomass are included in the total generation capacity but not explicitly modelled on an hourly basis due to their relatively stable output.

In H2RES, electricity generation is structured using the “Genco” CSV file, which compiles detailed data on power plants in Italy. Power plants are aggregated by source type, with key parameters including initial

installed capacity (Table 3), maximum investment capacity, storage potential, efficiency, CO<sub>2</sub> emissions, and decommissioning rates. Constraints are applied to limit investments in fossil fuel-based technologies, ensuring a transition toward a more sustainable energy mix.

Table 4

Installed capacity and maximum allowed investments by 2050 for the considered energy sources. Values are model assumptions derived from the Italian National Energy and Climate Plan and adopted within the H2RES modelling framework [73].

Energy sources	Capacity [MW]	Investment in capacity by 2050 [MW]
Coal	7896.7	0
Gas	44,521.8	3000
Oil	2447.2	0
Biomass	3641	1000
Photovoltaic	20,860	43,000
Wind	10,680	14,000
Hydro (HDAM)	16,887.1	1000
Hydro (HROR)	5654	1000

Additionally, hydropower expansion is restricted to prevent excessive environmental impact (Table 4).

H2RES optimizes investment decisions in energy capacity expansion while maintaining Critical Excess Electricity Production (CEEP) within a predefined limit [67]. Technologies related to thermal energy production and PtH conversion are managed through the “flex-tech” file, which includes conventional boilers, heat pumps, and electric heating. Their respective capacities are detailed in Table 5. The model integrates cogeneration and PtH solutions, leveraging heat storage to enhance system flexibility. Furthermore, H2RES allows for the incorporation of hydrogen storage, fuel cells, heat pumps, and electrolyzers, specifying their capacity, cost, and efficiency [47].

To align with Italy decarbonization goals, H2RES incentivizes capacity investments exclusively for biomass-based boilers, while preventing the expansion of fossil fuel-based heating systems. Policy constraints include: emission limits and renewable energy quotas (% FER) for each year; CEEP capped at 5% of total energy production to minimize grid imbalances. In 2019, the renewable energy share was 35.5%, with targets set at 65% by 2030 and 100% by 2050 [68]. CO<sub>2</sub> emissions in 2019 amounted to 170 million tons [69], with a 55% reduction target (relative to 1990 levels) by 2030 and a net-zero goal by 2050. The CO<sub>2</sub> emission cost is fixed at €25 per ton of CO<sub>2</sub>-equivalent and is assumed constant throughout the analysis period [70].

#### 4.2. Heating and cooling demand modelling in TRNSYS

Thermal sector is the most important sector in terms of final energy consumption, with over 40% for civil uses. Climate control (cooling and heating) accounts for 67.3% of total energy consumption, with about 50% of the demand met through natural gas.

To perform the analysis of the residential heating and cooling demands, the Italian building stock has been categorized based on climatic class, building size and construction period, identifying three reference building types (single-family, small apartment buildings, and tower buildings). Buildings with two types of roofing (flat and with habitable attics) were also considered for the single-family house and small apartment building types. The building types included in the dynamic simulation were chosen to balance model accuracy with computational efficiency when replicating the residential sector thermal energy demand. Italy features a diverse range of buildings constructed in different years with significant structural variations. However, it was possible to approximate this diversity by selecting a few types that are highly representative of the country's main climate zones. As shown in Fig. 6, simulations were conducted for each building type within the climate zones where they are representative. Additionally, the thermogrometric properties of each type were adjusted according to the local climate – a decision supported by a statistical analysis of Italy's construction characteristics [75].

The territory was divided into five climatic zones, from B to F [51], to assess thermal demand, and a representative city was chosen for each zone: Cuneo (zone F), Milan (zone E), Rome (zone D), Naples (zone C), and Palermo (zone B). Buildings were then classified based on the construction period (pre/post 1961) and materials used. For buildings constructed before 1946, wooden windows with single glazing and a thermal transmittance of 5.5 W/m<sup>2</sup>K were chosen, while for later buildings, windows with a transmittance of 2.82 W/m<sup>2</sup>K were selected,

**Table 5**

Installed electric heating capacity in Italy in 2019 by technology. Data compiled from Assoclisma, ENEL, and IEA statistics [74].

Technology	Capacity in 2019 [MW]	Source
Air-to-water heat pump	1000	Assoclisma
Air-to-air heat pump	7000	Assoclisma
Geothermal heat pump	1000	Enel
Electric boiler	8600	IEA

**Table 6**

Capacity investments by 2050 for non-programmable sources by scenario.

Energy source	Scenario 0	Scenario 1	Scenario 2	Unit
Power generation from solar	339,803	324,653	204,913.95	MW
Power generation from wind	70,837	107,679	133,426.37	MW
TOTAL	410,640	432,332	338,340.32	MW

specifically aluminium frames without thermal break and double glazing.

The clustering activity led to a building type matrix, inspired by the TABULA project [75], consisting of 30 different elements, each of which was simulated in TRNSYS to assess the annual heating and cooling demand. These 30 clusters were representative of the total number of buildings assumed to be inhabited in Italy, equal to approximately 11 million, according to the ISTAT database [76]. Although the adopted approach relies on a limited number of representative building types, this archetype-based clustering is a standard methodology in large-scale building-stock modelling and energy-system analysis. Archetype-based representations are widely used in national and European building stock models to balance data availability, computational feasibility, and representativeness. Previous studies have shown that a limited number of carefully selected archetypes can reproduce aggregated residential energy demand with acceptable accuracy when validated against statistical datasets [77,78]. The TABULA/EPISCOPE typologies adopted in this work cover the majority of the Italian residential floor area and have been extensively applied in comparative and policy-oriented studies [79].

Before the simulation, geometric models of the buildings were constructed using Google SketchUp, utilizing data on height, window area, and perimeter obtained from Google Earth (Fig. 6).

Once the building model was created in Google SketchUp, all related information was transferred to the TRNSYS software. After importing the various geometries into TRNBuild and determining the thermal and hygrometric characteristics of the numerous building clusters, these models were integrated into TRNSYS with other models, referred to as “types” which allow for accurate dynamic thermal demand simulation for heating and cooling by coupling building and thermal system and considering different and variable external climatic conditions.

Moreover, for an accurate demand calculation, different heat gains from occupants and from electrical and electronic equipment were considered, along with occupancy profiles for various resident types, different set points, and seasonal variations for each climatic zone, following similar approaches in previous studies [44].

The analysis conducted in TRNSYS produced 30 thermal demand profiles and 30 cooling demand profiles, corresponding to each element of the 30 within the building type matrix. Each calculated profile was multiplied by the number of buildings with the same characteristics within the same climatic zone, allowing for the calculation of total consumption profiles for each area and consequently for the entire country. The results obtained were validated by comparing the aggregated annual heating and cooling energy consumption derived from the TRNSYS simulations with national statistics provided by the Odyssey-Mure database [80] and ENEA [81]. The comparison shows that the simulated values fall within the expected range reported for archetype-based residential energy models, confirming that the selected building clusters provide a realistic and representative approximation of the Italian residential sector at national scale.

Regarding heating demand, an additional factor was added for domestic hot water consumption, which amounts to approximately 1000 kWh per person per year for private residences. With an estimated population of about 59 million people in Italy, the total hot water consumption equates to 59 TWh per year, or about 6735 MWh per hour (average power). This demand is considered constant throughout the year, leading to an annual thermal energy requirement for residential use of 487.7 TWh, significantly higher than the residential cooling

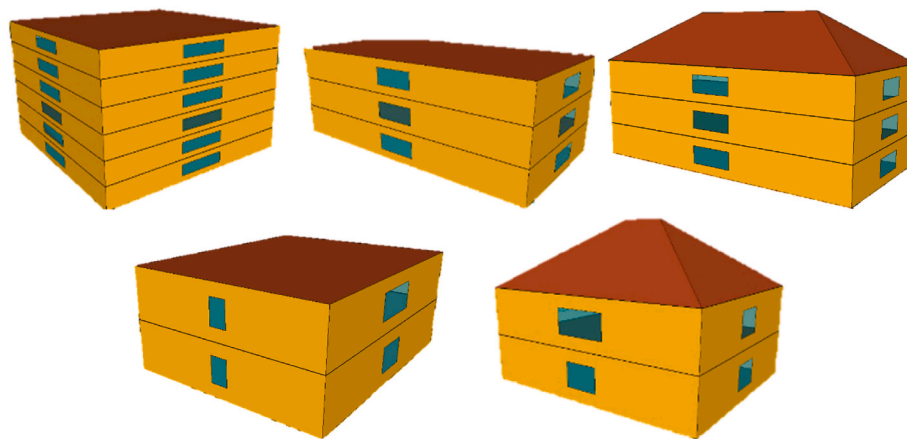


Fig. 6. Clusters of buildings created in Google SketchUp.

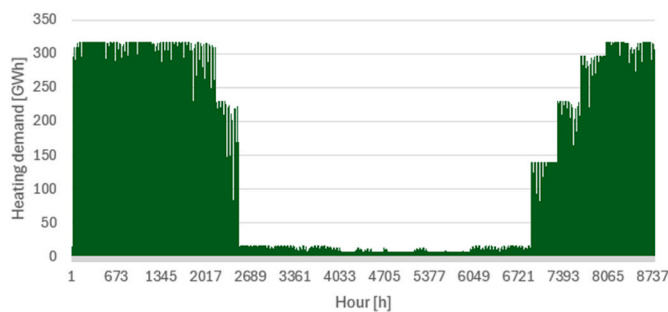


Fig. 7. Annual heating demand of Italian residential sector.

demand of 10 TWh per year. Figs. 7 and 8 show, respectively, the simulated heating demand profile obtained on both annual and hourly basis. The baseload is due to the DHW consumption of residential users.

Fig. 9 shows the dynamic profile of the cooling demand during the year for the residential sector. Also in this case the trend is perfectly in line with the expected results due to the peaks in high summer season and a decrease of the residential cooling demand during holidays time (usually around two weeks for Italians). Additionally numerical results are calibrated against annual values reported in the Odyssey-Mure database [80].

Once the heating and cooling profiles were obtained, they were integrated in H2RES, assuming 1% annual decrease in thermal demand for heating due to the rising temperatures, and a 1% annual increase in cooling demand. These values are consistent with national projections

for Italy and with the expected gradual shift of Mediterranean climatic conditions toward milder winters and warmer summers.

The applied trends of decreasing heating demand and increasing cooling demand are intended to represent, in an aggregated manner, the main implications of climate change on residential energy needs. Multiple European and Italian studies consistently indicate that future climate conditions will lead to reduced space-heating demand and a significant growth in cooling requirements, particularly in Mediterranean regions [82,83]. These studies typically report cumulative changes of 15–30% by mid-century, corresponding to average annual variations in the order of 0.5–1.5%, placing the adopted 1% assumption within the lower bound of published projections [84].

Climate change can also affect the performance of heating technologies, especially air-source heat pumps, whose efficiency depends on ambient temperatures. Existing literature suggests that rising winter temperatures generally improve average heat-pump performance, while increasing summer cooling operation [85,86].

However, a fully climate-responsive modelling of building envelopes and heat-pump performance would require re-running dynamic simulations under multiple future weather scenarios and lies beyond the scope of this system-level optimization study. The objective here is to provide representative hourly demand profiles suitable for long-term energy system planning rather than predictive assessments of climate impacts. Previous studies have shown that while climate change affects absolute demand levels, it does not significantly alter the relative behaviour of decarbonization scenarios or the dominance of electrified heating solutions [87].

To assess the impact of different constraints on the future evolution of the Italian energy system, three scenarios were selected and simulated

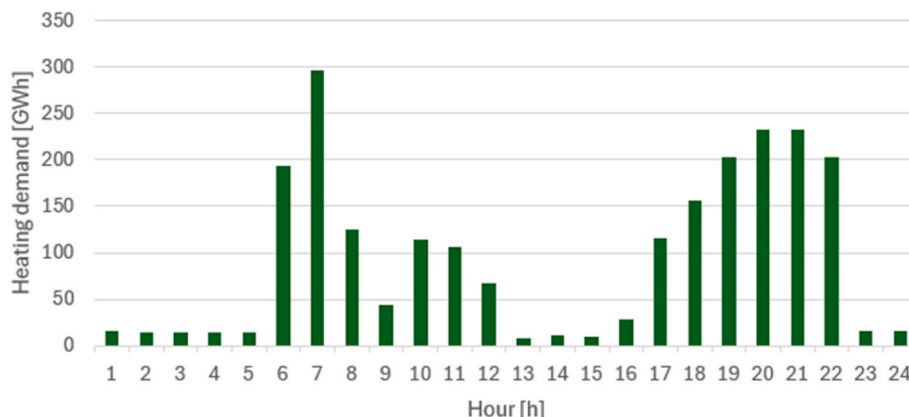


Fig. 8. Daily heating demand of Italian residential sector (typical day in January).

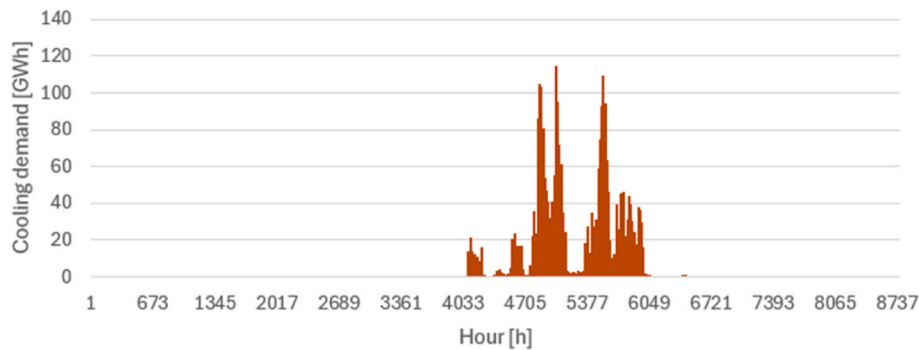


Fig. 9. Annual cooling demand of Italian residential sector.

using H2RES. These scenarios explore alternative energy mix configurations, particularly in the thermal sector, which remains one of the most environmentally impactful and difficult to decarbonize. The scenarios were chosen based on their relevance to key policy objectives, including renewable energy integration, emissions reduction, and energy system flexibility. Each scenario complies with national and European regulations and aims to identify feasible pathways toward achieving Italy decarbonization goals.

Although all scenarios pursue deep decarbonization, they differ in the degree of electrification and in the role assigned to solid biomass in the residential heating sector, allowing the analysis to capture a range of policy options rather than a single prescriptive pathway.

The three selected scenarios reflect varying levels of ambition in transitioning away from fossil fuels in the heating sector:

- Scenario 0 (Baseline - NT Italia Projection): This scenario represents the National Trend Italy (NT Italia) projection, where renewable energy investments follow current policies. The transition occurs gradually, with a moderate electrification rate and a growing share of biomass in the thermal sector.
- Scenario 1 (Biomass Restriction for Heating): Recognizing the sustainability concerns related to biomass use, this scenario limits its contribution to heating by imposing an upper bound on the share of solid biomass that can be used for individual residential heating. Biomass is therefore reduced but not completely excluded and can still contribute to the heating mix as a complementary option. This scenario is intended to reflect policy approaches that aim to restrict biomass use due to concerns about resource availability, local air quality, and biodiversity impacts, without enforcing full fuel switching.
- Scenario 2 (Full Electrification of Heating): This scenario envisions a complete transition to electricity-based heating, relying solely on heat pumps and electric boilers. It maximizes renewable electricity utilization while eliminating biomass combustion.

## 5. Results

This section presents the results from the economic optimization performed in H2RES coupled with dynamic residential heating and cooling demand profiles integrated from TRNSYS for all the scenario discussed in the *Case Study* section.

### 5.1. Scenario 0

In this scenario, capacity investments align with the National Trend Italy (NT Italia) projections. As illustrated in Fig. 10, achieving the defined energy transition targets requires substantial investments in renewable energy sources, with a particular emphasis on non-dispatchable technologies such as photovoltaics and wind power. Among these, solar photovoltaics emerge as the primary technology for

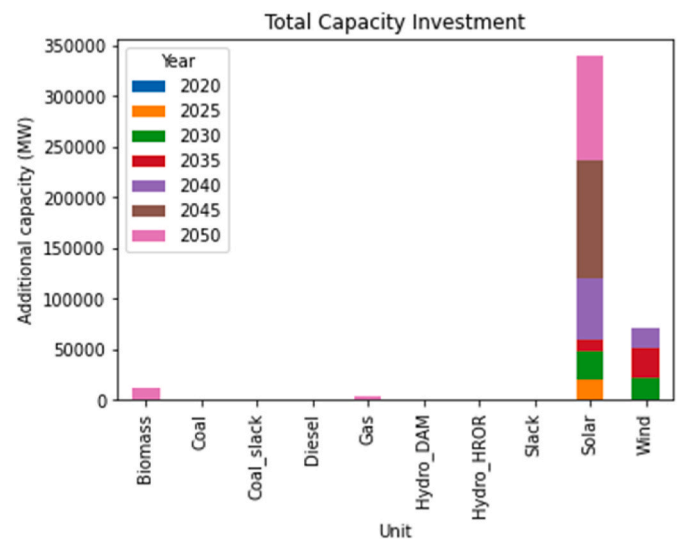


Fig. 10. Capacity investments [MW] (scenario 0).

future deployment, owing to Italy's high solar potential and the substantial remaining capacity for expansion. Wind energy is also expected to play a significant role in the renewable energy mix.

While hydropower remains crucial for meeting peak electricity demand, its expansion is severely constrained by the limited availability of new sites for further development in Italy. Additionally, biomass contributes a relatively small share of the energy supply, primarily due to low initial installed capacity and modest planned investments in biomass power plants within Italy's energy strategy.

This scenario simulates a transition marked by a gradual decline in fossil fuel reliance and a corresponding increase in renewable energy integration. Software projections from 2020 to 2050 (Fig. 11) indicate a steady increase in electricity generation, driven by growing electrification in the heating and transport sectors. While improvements in energy efficiency are expected to mitigate some of the additional electricity demand, the overall electrification trend is anticipated to significantly increase total electricity consumption.

Notably, despite the rise in electricity demand, the total final energy demand is projected to decrease. This reduction is attributed to the higher efficiency of electrified technologies compared to conventional fossil-fuel-based systems. If this electrification trend is coupled with substantial renewable energy expansion, the projected growth in electricity generation can be considered sustainable, ensuring alignment with long-term decarbonization targets. This is further reflected in a substantial decline in CO<sub>2</sub> emissions from the power sector by 2050.

Nonetheless, the rise in production from non-programmable renewable sources presents the challenge of overgeneration – electricity generated that cannot be directly utilized. Therefore, for an

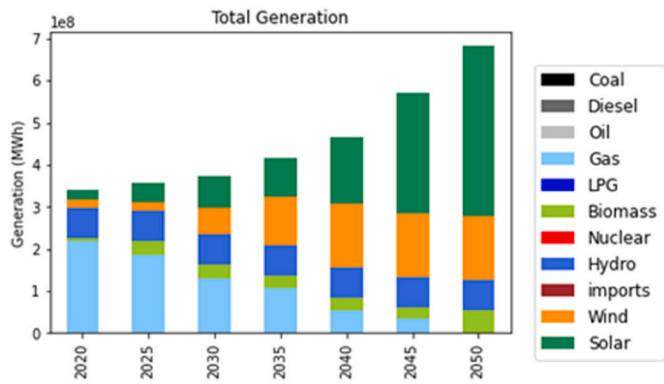


Fig. 11. Annual electricity generation by source with projections for 2050 (scenario 0).

effective energy transition, it is crucial to include PtX technologies, which facilitate the conversion, storage, and reconversion of excess electricity for use in other sectors, such as transport and heating. H2RES anticipates an initial utilization of excess energy to produce heat or hydrogen, followed by a significant increase in the use of electric vehicles for energy storage. This is largely due to the current low availability of electric cars, which is expected to rise substantially in the coming

years (see Fig. 12). With these technologies, a substantial reduction in critical excess electricity production is anticipated (see Table 8), well below the imposed limit of 5%.

As for the thermal sector, the evolution of energy sources for individual heating will result in a slow decrease in the use of gas. As shown by Fig. 13, while gas will still be present by 2050, its usage will be

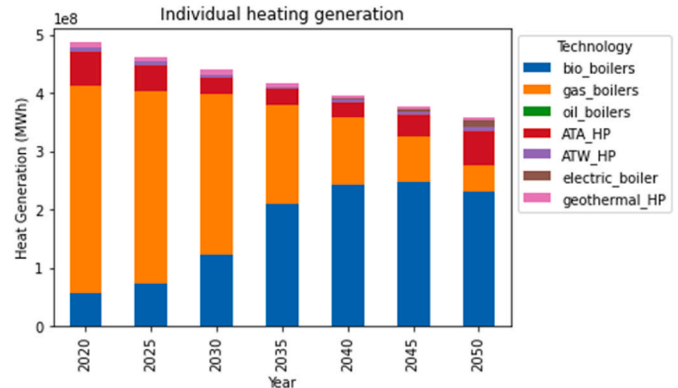


Fig. 13. Evolution of individual heating generation by 2050 (scenario 0).

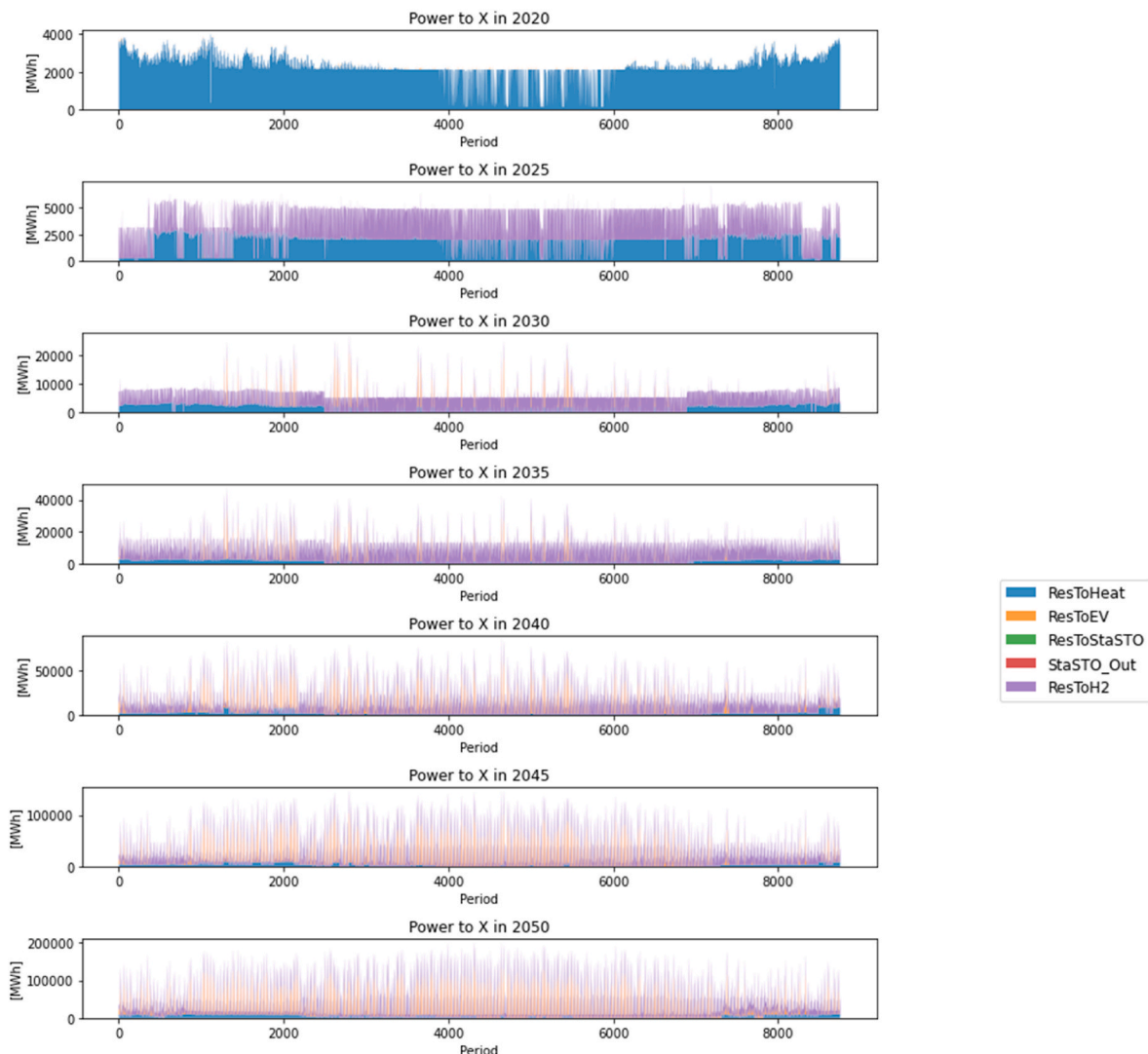


Fig. 12. Evolution of power-to-X technologies (scenario 0).

significantly lower, offset by a substantial increase in the use of biomass (in the form of firewood or pellets), which will become the primary energy source. A smaller share of heat will be produced by air-to-air heat pumps (see Table 7).

The reliance on biomass as the main renewable source for heating presents challenges due to deforestation and the loss of biodiversity that its widespread use can cause.

### 5.2. Scenario 1: limiting the use of biomass for heating

Limiting biomass usage is essential for achieving energy sustainability. Biomass is classified as:

- “residue-based biomass”, which refers to residual biomass that allows for the burning of wood that would otherwise go to waste, including material that may already be on the ground due to events like windstorms.
- “non-sustainable (roundwood) biomass”, associated with the cutting of trees to produce energy, which contributes to deforestation.

If the biomass is harvested responsibly, limitations on its use may be avoided. To account for this, only the fraction of biomass derived from residues is considered over the total useable biomass. When this percentage exceeds a predetermined threshold, no restrictions will apply. Conversely, if it falls below that value, the generation of heat for individual heating from this source will be limited for each period.

Assuming a scenario where this percentage exceeds 50%, we propose a limitation on biomass use to produce a maximum of 40% of the total heat demand for individual heating by 2050, with gradual adjustments in the preceding years. This scenario shows, in the heating sector, a more gradual increase in biomass usage that remains less than the previous scenario (Fig. 14). To compensate for this shortfall and meet decarbonization targets, H2RES anticipates an increase in production from air-to-air and air-to-water heat pumps to provide over half of the total thermal demand by 2050, at the expense of electric boilers with lower efficiencies (see Table 7).

The critical excess of electricity produced (CEEP) in this scenario is higher than in the previous one (see Table 8). This increase is mainly due to the reduced reliance on biomass in the thermal sector, leading to greater use of heat pumps and, consequently, an uptick in total electricity production to meet the demand. Since it is crucial to maintain the established percentage of renewables in the energy mix, this has resulted in increased investments in solar and wind energy compared to Scenario 0, amounting to 21.692 MW, as shown in Table 6.

### 5.3. Scenario 2: Total electrification of individual heating systems

Scenario 2 envisions complete electrification of the heating system, utilizing only electric boilers and heat pumps. Individual heating generation by 2050 will be completely carried out by heat pumps, in particular air-to-air (ATA) heat pumps and, to a lesser extent, by air-to-water (ATW) and geothermal heat pumps (Fig. 15). For heat pumps, in fact, total capacity investments are expected to be much higher by 2050 (see Table 7).

In this scenario, CEEP has been significantly reduced (see Table 8), thanks to the notable increase in Power-to-Heat (PtH) technologies compared to other options. This electrification represents one of the

**Table 7**  
Capacity investments by 2050 in the heating sector by scenario.

Technology	Scenario 0	Scenario 1	Scenario 2	Unit
ATA	8868.14	20,686.73	84,169.54	MW
ATW	621.5	16,642.35	23,300	MW
Biomass	83,726.93	41,525.85	-	MW
Geothermal	-	-	5981.39	MW

**Table 8**  
CEEP value by Scenario.

CEEP	Scenario 0	Scenario 1	Scenario 2	Unit
	1.04%	2.59%	0.06%	%
	8.17	20.97	0.43	TWh

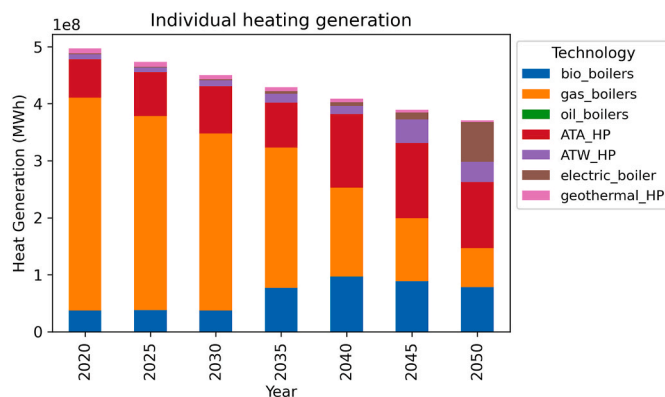


Fig. 14. Evolution of individual heating generation by 2050 (scenario 1).

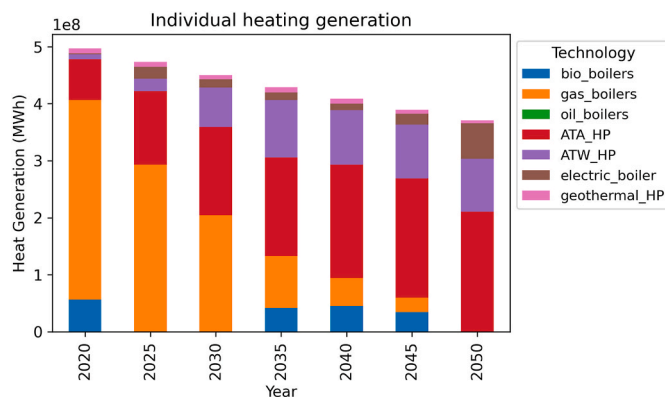


Fig. 15. Evolution of individual heating generation by 2050 (scenario 2).

most effective solutions for utilizing a large portion of the energy produced by renewable sources and reducing the critical excess of energy generated. Fig. 16 shows that by 2050 there will be less excess energy, and this will be regulated through the heat pumps themselves, which will be among the most widely used PtX technologies.

Regarding investments in non-programmable renewable energy, contrary to expectations, there is a decrease in total MW due to a 40% reduction in solar investments (see Table 6). In the previous case, H2RES, with no restrictions on renewable investments, focused on the most cost-effective technology to complement biomass usage, specifically photovoltaics. Since photovoltaics are less productive in the winter, this leads to increased investments in total capacity to meet as much demand as possible, considering the limited contribution from biomass. However, in this case, with biomass not being useable, it is necessary and more cost-effective to enhance wind power capacity compared to photovoltaics, given its energy production profile, which aligns better with heating demands during periods of low solar radiation.

To equally compare results across all the simulated scenarios, Table 9 provides a harmonized cross-scenario comparison of the most policy-relevant outputs of H2RES: total discounted system cost (objective value), CO<sub>2</sub> emissions, renewable electricity share, and the magnitude of critical excess electricity production (CEEP) as an indicator of renewable integration and curtailment. Specifically, CO<sub>2</sub> reduction is computed

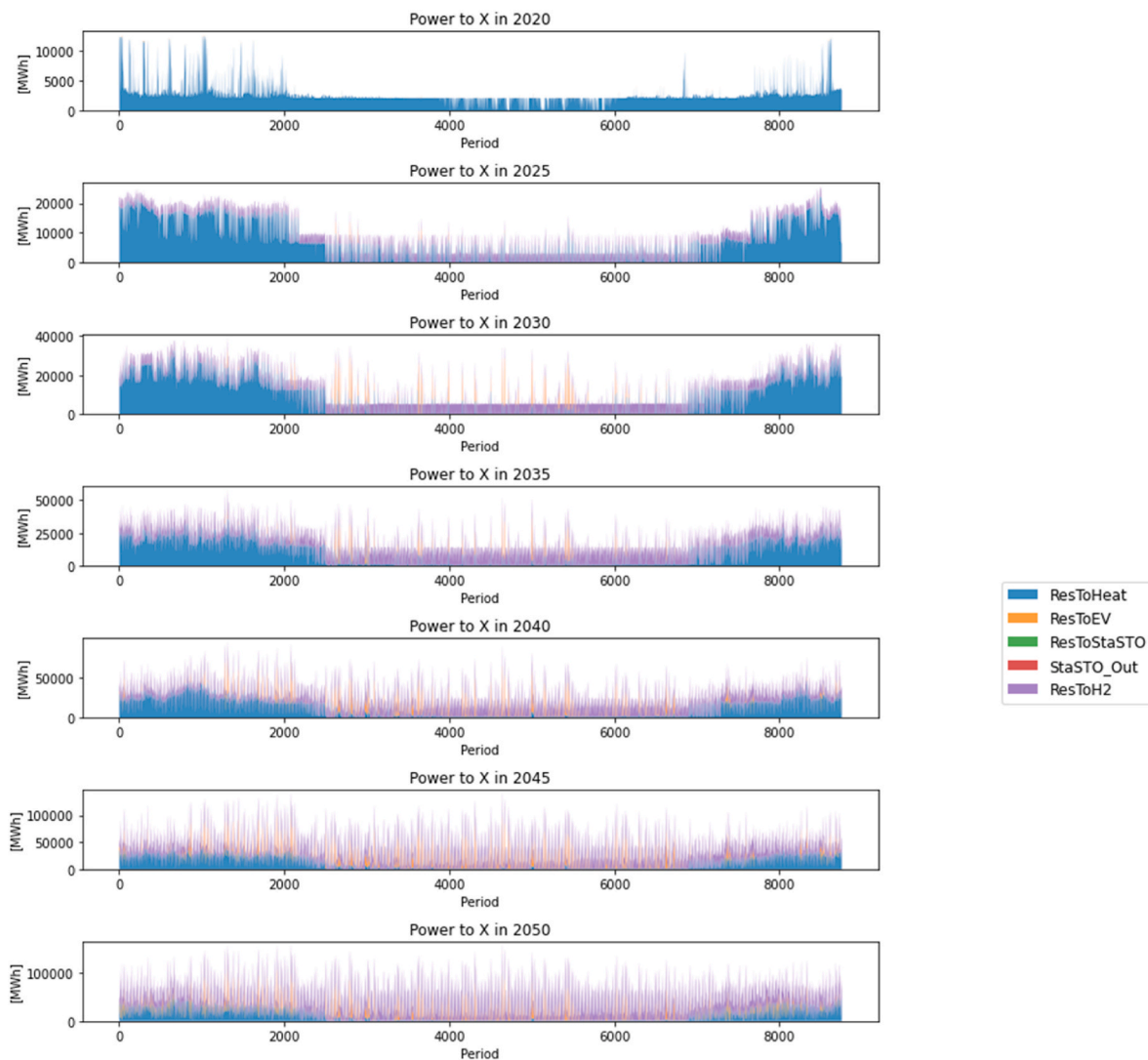


Fig. 16. Evolution of power-to-X technologies (scenario 2).

Table 9

Cross-scenario comparison of total discounted system cost, CO<sub>2</sub> emissions, renewable electricity share, and critical excess of electricity production (CEEP) in 2050.

Scenario	Total system cost (NPV), B€	CO <sub>2</sub> 2020 (Mt)	CO <sub>2</sub> 2050 (Mt)	CO <sub>2</sub> reduction (%)	RES share 2050 (%)	CEEP 2050 (TWh)	CEEP 2050 (%)
Scenario 0	275.111	170.0	17.0	90.0	100	44.33	5.0
Scenario 1	277.882	170.0	17.0	90.0	100	42.54	5.0
Scenario 2	308.189	170.0	4.48	97.36	100	21.52	2.6

relative to 2020. CEEP share is computed relative to total electricity demand plus flexible sinks (power-to-heat, EV charging, stationary storage charging, and power-to-H<sub>2</sub>).

A first key outcome is that all three scenarios achieve a fully renewable electricity mix by 2050 (100% RES share). This indicates that, under the imposed policy constraints and techno-economic assumptions, the optimization consistently finds a pathway in which fossil electricity generation is fully displaced by renewable technologies. However, a fully renewable electricity mix does not automatically translate into near-zero system-wide CO<sub>2</sub> emissions. The scenarios differ substantially in residual emissions, showing that decarbonization is not driven only by the supply-side electricity mix but also by how final energy demand—especially heat—is served and constrained.

In Scenarios 0 and 1, CO<sub>2</sub> emissions fall from 170 Mt in 2020 to 17 Mt in 2050 (90% reduction). The similarity of these two outcomes suggests that the additional constraint defining Scenario 1 alters the optimal

solution only marginally at the level of aggregated system indicators. In other words, the model can satisfy the Scenario 1 restriction without a major reconfiguration of the overall system cost or residual emissions compared to the baseline. This is still an important result: it indicates that certain policy or resource constraints may be system-manageable within the optimization space, producing limited macro-level penalties when sufficient flexibility exists elsewhere in the system.

Scenario 2 stands out as a more structurally different pathway. It reaches 4.48 Mt CO<sub>2</sub> in 2050, corresponding to a 97.4% reduction relative to 2020. This deeper abatement comes with a higher total system cost (+12% compared to Scenario 0), illustrating a clear cost–abatement trade-off. Interpreting this trade-off is crucial for the reviewer’s concern: the model does not simply “produce renewable electricity”; it identifies a least-cost configuration subject to constraints, and more stringent decarbonization requirements (or stronger electrification-type constraints) typically require additional

investments, technology substitutions, and/or more expensive marginal abatement options, which become visible in the objective value.

Importantly, Scenario 2 also shows markedly better renewable integration: CEEP drops from about 44.3 TWh (5%) in Scenario 0 to 21.5 TWh (2.6%) in Scenario 2. Since CEEP represents electricity production that cannot be absorbed by demand or available flexibility options, lower CEEP indicates that Scenario 2 achieves a better temporal match between renewable generation and consumption. This implies that the higher cost of Scenario 2 is not driven by inefficient overbuilding with large curtailment; rather, it is consistent with a system that uses renewable generation more effectively, likely through a different combination of demand electrification, flexible loads, and capacity mix. In practical terms, the scenario appears to shift the system toward a configuration where renewable output is more frequently “useful,” which reduces curtailment and can improve operational efficiency, even if the overall system cost increases due to the investments and constraints required to eliminate additional residual emissions.

Taken together, Table 9 highlights three general insights. First, electricity-sector decarbonization (100% RES electricity) is achievable across all pathways under the assumed boundary conditions. Second, system-wide CO<sub>2</sub> outcomes are highly sensitive to end-use structure and constraints, not just supply mix; this is why Scenario 2 achieves substantially lower residual emissions. Third, system cost and integration indicators do not move in the same direction: Scenario 2 is more expensive but also reduces curtailment (lower CEEP), suggesting that stricter decarbonization can coincide with improved operational alignment, even while raising total cost. This underscores the value of reporting emissions and cost consistently across scenarios: it makes visible the trade-offs between economic effort, decarbonization depth, and system integration performance.

In this study, system flexibility is primarily provided through electric storage technologies, including batteries, vehicle-to-grid integration, and hydrogen-based storage. Thermal storage technologies, such as hot-water tanks or chilled-water buffers, were not explicitly modelled within the H2RES framework. While these solutions can play a relevant role in absorbing photovoltaic surpluses and temporally shifting heating and cooling loads, their explicit representation would require additional assumptions on storage sizing, control strategies, and building-level integration.

Nevertheless, thermal storage represents a complementary flexibility option that could further reduce peak electricity demand and mitigate renewable curtailment, especially in highly electrified heating scenarios. Its potential role is therefore acknowledged as an important extension of the present work and a promising direction for future research, particularly in more detailed or sector-specific modelling frameworks.

#### 5.4. Sensitivity analysis and discussion

To address the robustness of the proposed fully renewable energy system transition for Italy, two sensitivity analyses were performed, focusing on (i) the role of carbon pricing under an ETS-like mechanism and (ii) the impact of building energy refurbishment on residential heating demand. These analyses were designed to assess how strongly the long-term system configuration and emissions trajectory depend on policy and demand-side assumptions.

##### 5.4.1. Sensitivity to carbon pricing (ETS)

To assess the influence of carbon pricing assumptions on system evolution, a sensitivity analysis was conducted using three alternative CO<sub>2</sub> price trajectories representing low (fixed at 25 €/tCO<sub>2</sub>), medium (from 50 €/tCO<sub>2</sub> to 200 €/tCO<sub>2</sub>), and high (from 100 €/tCO<sub>2</sub> to 400 €/tCO<sub>2</sub>) carbon price environments. These trajectories span a wide range of values, thereby testing the robustness of the model outcomes to this key economic parameter.

Fig. 17, Fig. 18 and Fig. 19 present the resulting electricity

generation mix (top row) and individual heating generation by technology (bottom row) across the three CO<sub>2</sub> price scenarios.

The most striking result is the limited sensitivity of the electricity generation mix to the carbon price level. Across all three scenarios, coal-based generation is phased out early in the transition, primarily due to binding CO<sub>2</sub> emission caps and renewable energy targets rather than price effects. Gas-fired generation declines steadily over time, while wind and solar dominate the generation mix by 2040–2050. Hydro-power remains relatively constant, and electricity imports play only a marginal role in all cases.

Differences between scenarios are modest and mainly affect the timing of the transition. In the high CO<sub>2</sub> price case, gas generation declines slightly earlier and renewable capacity scales up marginally faster in the 2030–2035 period. Conversely, under the low CO<sub>2</sub> price trajectory, gas persists somewhat longer, resulting in slightly higher fossil-based generation in the mid-term. However, by 2050 the electricity mixes are nearly identical across all scenarios.

These results indicate that electricity decarbonization in the model is driven primarily by structural constraints – namely CO<sub>2</sub> emission caps and renewable penetration requirements – rather than by the carbon price signal itself.

The sensitivity to CO<sub>2</sub> price is somewhat more visible in the residential heating sector, though still limited in magnitude. In all scenarios, gas boilers are progressively phased out and replaced by electrified heating technologies, with heat pumps becoming dominant by 2050. Biomass remains constrained and never emerges as a major contributor, while electric boilers play only a marginal role.

Higher CO<sub>2</sub> prices lead to a slightly faster reduction of gas boiler use and a marginally earlier uptake of heat pumps, particularly in the early and mid-transition years. Under lower CO<sub>2</sub> prices, gas-based heating persists somewhat longer, resulting in a slower but still complete transition. Crucially, however, the final outcome is the same across all scenarios: full electrification of residential heating by 2050.

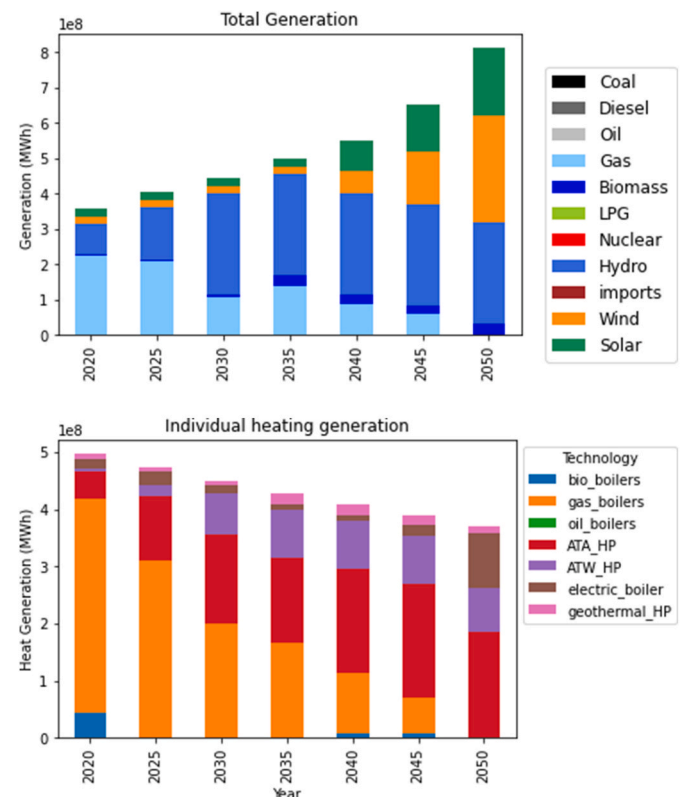


Fig. 17. Sensitivity analysis: Total generation and individual heating generation in the low ETS case.

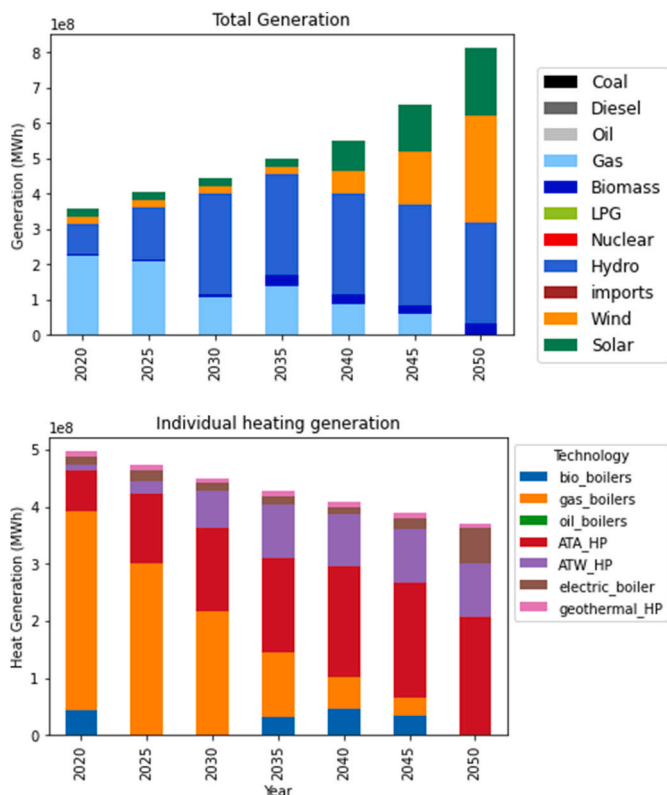


Fig. 18. Sensitivity analysis: Total generation and individual heating generation in the medium ETS case.

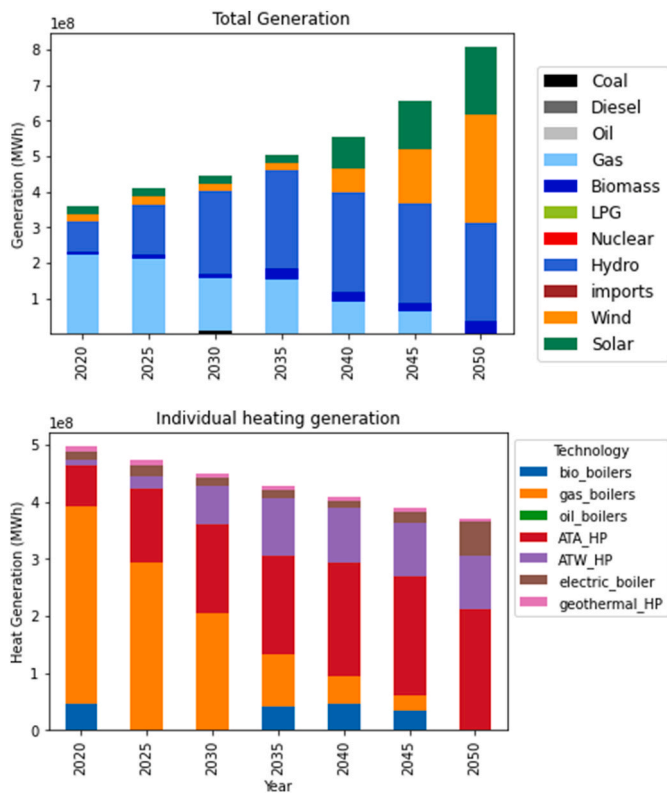


Fig. 19. Sensitivity analysis: Total generation and individual heating generation in the high ETS case.

This behavior reflects the fact that the heating transition is largely enforced by exogenous policy constraints on technology shares (e.g., electrification and renewable heating targets), with the carbon price acting mainly as a secondary accelerator rather than a decisive driver.

Overall, the ETS sensitivity analysis shows that higher CO<sub>2</sub> prices primarily influence the pace of the transition rather than its direction. Even under conservative carbon price assumptions, the model achieves deep decarbonization of both electricity and heating sectors, driven by binding policy constraints and long-term structural targets. Higher carbon prices mainly reduce transitional fossil fuel use and slightly accelerate early investments, without altering the long-term system configuration.

#### 5.4.2. Sensitivity to building refurbishment and heating demand reduction

To explicitly address the role of building energy renovation, an additional sensitivity analysis was carried out by introducing a progressive reduction in residential heating demand over the modeling horizon. This reduction reflects the expected impact of large-scale refurbishment policies and stricter building energy performance standards, increasingly required by European regulations for existing buildings. Therefore, a progressive reduction in space-heating demand to meet the 30% target in alignment with EU renovation-wave expectations is integrated [88].

Fig. 20 shows individual heating generation by technology in the refurbishment scenario to compare it with the reference scenarios in Figs. 13–15. The most immediate and expected effect is a substantial reduction in total useful heat demand over time. By 2050, total individual heating demand decreases from approximately 3.6–3.7 × 10<sup>8</sup> MWh in the reference case to about 2.6 × 10<sup>8</sup> MWh in the refurbishment case, corresponding to a reduction of roughly 30%. This magnitude is fully consistent with the imposed renovation trajectory and confirms the correct implementation of demand-side efficiency measures [89,90].

Importantly, while the scale of the heating system is reduced, its structural evolution remains unchanged. In both cases, gas boilers are phased out early in the transition, biomass plays only a marginal and declining role, and electrified heating – dominated by heat pumps – becomes the prevailing solution by 2040–2050. The introduction of refurbishment does not alter the ranking or relative attractiveness of heating technologies, indicating that renovation policies reduce the size of the problem rather than changing the nature of the decarbonization pathway.

The impact on heat pump deployment is particularly relevant. In the reference case, heat pumps supply approximately 3.1 × 10<sup>8</sup> MWh of useful heat in 2050, while this value drops to about 2.2 × 10<sup>8</sup> MWh when refurbishment is considered. This translates into a reduction of roughly 25–30% in required heat pump generation and, consequently, installed capacity. Nevertheless, full electrification of the residential heating sector is preserved in both cases, reinforcing the robustness of

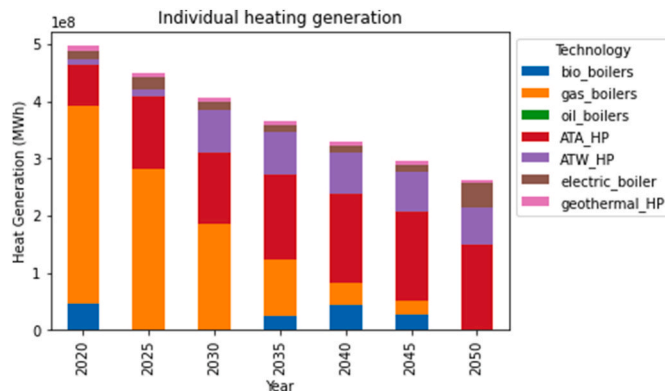


Fig. 20. Sensitivity analysis: Reduction of the energy demand of residential sector.

the electrification strategy.

Notably, the timing of fossil fuel phase-out is largely unaffected by demand reduction. Gas boilers disappear at approximately the same point in the transition (around 2035–2040) in both scenarios, indicating that refurbishment does not delay decarbonization. Instead, it alleviates system stress by lowering electricity demand and capacity requirements, without weakening the policy-driven electrification trajectory.

From a sustainability perspective, refurbishment further reduces the absolute contribution of biomass, which never becomes dominant in either scenario. This supports the conclusion that large-scale biomass deployment is neither necessary nor desirable for residential heating, and that the combination of energy efficiency and electrification represents the most consistent long-term pathway.

Overall, this sensitivity analysis demonstrates that accounting for building renovation significantly lowers total heating demand, electricity consumption, and required heat pump capacity, while leaving the qualitative transition pathway unchanged.

Beyond the residential heating and electricity sectors explicitly modelled in this work, achieving climate-neutral energy systems requires coordinated integration of industry, transport, and fuel sectors. Recent smart energy systems studies highlight that large-scale balancing of variable renewable generation increasingly relies on cross-sectoral storage, hydrogen, and demand-shifting strategies spanning electricity, heat, fuels, and industrial processes [91]. While the present analysis focuses on residential thermal demand and power-system interactions, the Italian case study provides insights that are directly relevant to this broader context.

In particular, the strong electrification of heating and the associated flexibility needs identified here are consistent with the challenges of energy balancing in climate-neutral smart energy systems, as discussed in recent international literature. Extending the present framework to explicitly include industrial heat, transport fuels, and hydrogen end-use would represent a natural and valuable direction for future research. However, while future fossil fuel prices remain uncertain, existing literature indicates that their variation primarily shifts system costs rather than qualitative transition pathways [47]. In line with recent findings for Italy and other European systems, the results presented here are robust with respect to reasonable fossil price assumptions, as the decarbonization trajectory is predominantly driven by structural constraints and electrification targets rather than by fuel price signals.

## 6. Limitations of the study

The present analysis is subject to several limitations that should be considered when interpreting the results. First, while residential heating and cooling demand is represented through detailed dynamic simulations, other demand sectors are modelled using aggregated profiles scaled over time. This choice reflects data availability and the system-level scope of the study.

Second, climate change impacts on thermal demand and heat pump performance are incorporated through simplified trend adjustments rather than through full climate-responsive building simulations under future weather scenarios. This approach is intended to capture first-order effects while maintaining consistency across scenarios.

Third, the hourly electricity demand profile is assumed to retain the shape of the 2019 pre-pandemic year and is scaled over time according to national projections. Potential future changes in load patterns driven by electric vehicles, demand response, or industrial electrification are not explicitly modelled.

Fourth, biomass availability is addressed through policy-based constraints rather than through a detailed representation of biomass supply chains and competing uses.

Finally, the present work focuses on deterministic, long-term energy system optimization and explores the sensitivity of results to key structural assumptions such as renovation rates, carbon pricing, and fuel costs. Other sources of uncertainty – such as probabilistic

representations of technology performance, disruptive events, extreme climate phenomena, supply-chain shocks, or abrupt policy changes – are not considered, as their analysis would require fundamentally different modelling approaches, including stochastic optimization or risk-based frameworks. Addressing these aspects lies beyond the scope of the present study and represents an important direction for future research.

## 7. Conclusions

Energy planning is an invaluable tool for analysing future energy scenarios, providing critical insights into system evolution and policy impacts. However, it requires a substantial volume of data and the integration of multiple interdependent variables, making it a complex and data-intensive process. One of the most challenging aspects is modeling thermal demand, which is particularly difficult due to limited data availability in the literature and the wide range of influencing factors. A precise and dynamic demand profile is essential for accurate scenario analysis, and simulation tools such as TRNSYS offer a robust approach for generating realistic thermal demand projections.

This study highlighted how achieving decarbonization goals goes hand in hand with the transition towards the electrification of the energy system. The adoption of electricity-based technologies – particularly in heating and transport – leads to a reduction in emissions rather than an increase. However, this transition must be supported by substantial investments in renewable energy expansion, particularly in solar PV and wind power, as these will become the dominant sources of electricity generation. The forecasts generated by H2RES align with Italy's Long-Term Energy Strategy, which projects that, by 2050, electricity generation must more than double compared to pre-pandemic levels, reaching 600–700 TWh, with renewable energy supplying nearly 100% of demand. Both H2RES and the Italian strategy identify solar PV as the primary renewable energy source, with wind power – particularly offshore wind – playing a complementary role. According to both projections, installed renewable capacity is expected to reach between 200 and 300 GW, a substantial increase compared to the 30.3 GW of operational solar capacity as of 2023.

A major challenge associated with high levels of solar and wind power penetration is their non-dispatchable nature, which can lead to critical excess electricity production (CEEP) if generation surpasses real-time demand and storage or export options are unavailable. Addressing this issue requires the development of Power-to-X (PtX) technologies, which are examined in further detail in this study. Among the most promising PtX applications is Power-to-Heat, particularly due to the increasing role of heat pumps in the heating sector. The electrification of heating is not only a crucial step toward emissions reduction but also a necessary strategy for reducing reliance on biomass, which, while renewable, poses sustainability risks when overexploited. Furthermore, electric heating technologies offer superior efficiency compared to conventional methane-based heating systems: producing 1 MWh of electricity for heating purposes requires less primary energy than direct thermal generation from fossil fuels.

In a scenario where individual heating systems are fully electrified by 2050, investments in heat pump capacity would need to increase by approximately 100 GW. If biomass is integrated alongside heat pumps, this capacity requirement could be reduced by 30%. However, this approach necessitates careful consideration of biomass sourcing to prevent deforestation, which would counteract CO<sub>2</sub> absorption benefits.

Full electrification of the thermal sector also necessitates greater investment in wind power, as it is better aligned with winter heating demand patterns. Given the limited expansion potential of onshore wind, due to bureaucratic barriers and site availability constraints, offshore wind energy is expected to play an increasingly significant role.

While the 2050 decarbonization targets remain technically achievable, several key challenges must be addressed to ensure a successful transition:

- Permitting and bureaucratic barriers that slow down project development and investment in renewable energy infrastructure.
- The pace of renewable capacity expansion, which saw a notable increase in 2023, with an additional 5.7 GW of renewable capacity installed (5234 MW from photovoltaics and 487 MW from wind), as reported by Gaudi data from Terna.
- The development of energy balancing technologies, without which a fully renewable energy system cannot be realized.

### CRedit authorship contribution statement

**Francesco Calise:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation. **Francesco L. Cappiello:** Writing – review & editing, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Luca Cimmino:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis. **Neven Duic:** Writing – review & editing, Visualization, Supervision, Software, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Antun Pfeifer:** Writing – review & editing, Writing – original draft, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation. **Francesca Pugliese:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Investigation, Formal analysis, Conceptualization. **Maria Vicidomini:** Writing – review & editing, Supervision, Software, Resources, Investigation, Formal analysis, Conceptualization.

### 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.

### Nomenclature

#### Acronyms/Abbreviations

TRNSYS	Transient System Simulation Tool
H2RES	Energy planning optimization tool (open-source)
VRES	Variable Renewable Energy Sources
PtX	Power-to-X.
PtH	Power-to-Heat
EV	Electric Vehicle
CEEP	Critical Excess of Electricity Production
IEA	International Energy Agency
ISTAT	Istituto Nazionale di Statistica, the Italian national statistics institute
EUROSTAT	European statistical office.
SISTAN	Italian source for electric transport demand data

#### Symbols / Variables

$x_i$	Humidity ratio of the air node
$x_a$	Ambient humidity ratio
$x_{vent,k,i}$	Humidity ratio of the ventilation air
$M_{eff,i}$	Effective moisture capacitance of the air node
$W_{g,i}$	Internal moisture gains at the air node
$x_j$	Humidity ratio of an adjacent air node
$Q_{surf,i}$	Convective heat gain from surfaces at node “i.”
$Q_{inf,i}$	Heat gain due to infiltration at node “i.”
$Q_{vent,i}$	Heat gain due to ventilation at node “i.”
$Q_{cplg,i}$	Heat gain due to air exchange (coupling) between nodes at “i.”
$Q_{cg,i}$	Internal convective heat gains at node “i.”
$Q_{solar,i}$	Fraction of solar radiation entering through windows at node “i.”
$Q_{ISHCLi}$	Absorbed solar radiation by internal shading devices at node “i.”

#### Superscripts / Subscripts

i	Index for a specific node, thermal zone, or building element
j	Index for an adjacent or neighbouring node/zone
k	Index to differentiate among multiple components (e.g., ventilation streams) within a node
t	Technology index (used to denote different energy generation or conversion technologies in the optimization model)
p	Period or hour index (used when modeling hourly dispatch and operation in the optimization framework)
y	Year index (used for representing the time horizon in long-term energy planning)

#### Data availability

No data was used for the research described in the article.

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