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Article

District Heating Deployment and Energy-Saving Measures to Decarbonise the Building Stock in 100% Renewable Energy Systems

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Abstract: Achieving a zero-emission building heating sector requires numerous strategies and detailed energy planning, in order to identify the optimal decarbonisation pathway. This work aims to assess the impact of district heating expansion and the implementation of energy-saving measures on the decarbonisation of the Italian building stock by 2050, analysing their combined impact, reciprocal effects, and technical–economic implications on the entire national energy system. The scenarios have been implemented and simulated with the H2RES software, a long-term energy planning optimisation model, built for the Italian national energy system. Results indicate that it is possible to decarbonise the heating system in an efficient and cost-effective manner by the year 2040. Heat pumps represent the optimal technology at both centralised and decentralised levels. District heating expansion is a priority for the decarbonisation of the building stock, allowing us to reduce costs, exploit thermal storage systems and provide system flexibility. In the best scenario, 40% of the Italian heat demand can be supplied by fourth-generation district heating. Energy-saving measures can reduce heat demand and primary energy but at higher annual costs and with a significant increase in investment. The combined simulation of the strategies within an optimisation model of the entire energy system enables the accurate assessment of the real impact of the various measures, considering their reciprocal effects and technical–economic implications.

Keywords: fourth-generation district heating; long-term energy planning; power to heat; sector coupling; energy efficiency; carbon neutrality

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1. Introduction

There is a growing consensus among scientists, policymakers, and the general public on the need to achieve climate neutrality in the shortest possible time frame [1]. One of the most significant steps in the complex process of mitigating anthropogenic climate change is the transformation of fossil-based energy systems into 100% renewable energy systems [2].

Although several important goals have been established and there are energy and climate plans for decarbonisation in many countries, the level of investment by governments does not appear to be coherent, particularly in relation to the construction of new infrastructure [3].

Several studies have investigated 100% renewable energy systems, demonstrating that the complete decarbonisation of all energy sectors is technically feasible [4].

The building sector represents a significant contributor to energy consumption and greenhouse gas emissions, accounting for 40% and 36% of final energy consumption and carbon dioxide (CO_2) emissions in Europe, respectively [5]. Furthermore, the extensive use of gas boilers has a detrimental impact on urban air quality [6].

In order to mitigate the adverse effects of energy consumption and environmental impact, it is imperative to implement energy-saving measures [7]. In fact, the majority of buildings exhibit low energy performance levels, which is primarily attributable to the absence of regulatory directives pertaining to this matter at the time of their construction. A number of cost-effective measures for reducing emissions can be identified, all of which relate to improving the energy performance of buildings in order to minimise heating and cooling demand [8].

Furthermore, the European Union has endorsed the 'energy efficiency first' approach, which views energy demand reduction as the primary action with respect to improving supply efficiency and end-use electrification. Indeed, the achievement of net-zero energy buildings depends first and foremost on the implementation of energy-saving actions [9].

Nevertheless, additional pivotal interventions will be required to achieve the decarbonisation of the building stock. Heat pumps (HPs) will be the main technology for supplying heating demand through renewable sources [10]. Indeed, the advantage of such systems is that they are a high-performance technology that is already widely commercialised and cost-competitive [11].

For the heat pumps' deployment in the energy system, there are two main approaches: the first is a decentralised one, where each building is supplied by an individual system, and the second is a centralised one, where heat is distributed through a district heating (DH) network [12].

Fourth-generation DH, meanwhile, involves a low-temperature network that is capable of integrating renewable generation, including that which has been converted into heat energy through the use of heat pumps [13]. This concept has been introduced by Lund et al. [14] to define a smart thermal grid that can efficiently and economically supply heat demand, integrate renewable generation, provide system flexibility and be a key component in future smart energy systems.

The DH has indeed faced a reduction in temperatures as the generations have passed. The transition from third- to fourth-generation DH has lowered the supply temperature from around 100 °C to 50–60 °C [15]. This reduces heat losses, improves energy efficiency and allows for the integration of centralised HPs and thus the use of renewable electricity generation to supply the DH demand [16].

Switching from decentralised to centralised HPs allows the capacity of heating systems to be increased and their efficiency improved. HPs can be operated more flexibly by exploiting both the thermal inertia of the DH network and dedicated thermal storage systems [17]. Several studies show how this strategy is cost-effective and to be preferred where possible to individual demand [18], and how exploiting centralised HPs and thermal storage systems is a much more cost-effective solution than using electricity storage, such as lithium-ion batteries, for the integration of non-programmable renewables [19].

In order to assess the role of different technologies in future energy systems, it is necessary to determine the optimal implementation level of decarbonisation strategies [20]. Computational energy models represent essential tools for the energy planning process [21]. Bottom-up energy models allow us to evaluate the different feasible solutions for the decarbonisation process, by assessing several renewable and power-to-x technologies [22].

Among them, long-term optimisation models consider the entire energy transition pathway up to the target year [23]. These models seek to optimise both the operation of the technologies and the time over which these technologies are installed, taking into account the variation of the installation cost over time [24].

Among long-term optimisation models, the principal distinction can be made between myopic optimisation and perfect foresight [25]. In the first case, the tool optimises the configuration at each step without knowledge of what will occur in subsequent steps [26]. In models of perfect foresight, all techno–economic parameters are known in advance, and the tool makes decisions throughout the optimisation period with complete information [27].

In recent years, several long-term energy models have been developed for the purpose of national energy planning. However, as demonstrated by Feijoo et al. [28], H2RES is the only open-source model that allows for the long-term optimisation of energy systems through the planning of investments and the operation of technologies, by combining hourly resolution for each simulation step, numerous power-to-X technologies and the possibility of implementing all energy sectors.

1.1. Literature Review

Several works in recent years have analysed the impact of DH deployment in energy planning on decarbonised energy systems.

In Ref. [29], they propose that the implementation of a DH network along with individual heat pumps in low-density residential areas would result in a reduction in energy consumption by 15% in comparison to a scenario based mainly on energy efficiency.

Xiong et al. [30] demonstrated that the deployment of DH can result in a reduction of primary energy for heating in China of up to 60%, while simultaneously reducing the overall system costs.

Sorknæs et al. [17] demonstrated the advantages of implementing fourth-generation district heating as part of the transition to a 100% renewable energy system for the Aalborg Municipality. Additionally, the utilisation of low-temperature DH in their study showed a reduction in both primary energy and costs, thereby providing system flexibility to integrate renewables.

Pakere et al. [31] analyse a development of DH systems integrating thermal storage, heat pumps and waste heat sources, providing a comprehensive assessment of their environmental impact.

In Ref. [32], Connolly et al. analysed the combined impact of DH implementation and the energy-saving (ES) measures. According to them, in order to accurately assess the true impact of energy savings and efficient heat supply, it is essential to consider these factors in a combined manner, taking into account the mutual effects.

Several works have discussed and demonstrated the importance of evaluating the combined effect of implementing energy-saving strategies and district heating network development. However, most studies do not investigate the best strategy to decarbonise the heating sector by contextualising it in a national energy model that describes the energy transition of all sectors.

To the best of the authors' knowledge, no studies in the literature have yet analysed this issue using a long-term optimisation model of the entire Italian energy system and evaluating the technical–economic effects of strategies on the building heating sector as well as on the entire Italian energy system.

This paper attempts to bridge this gap by analysing the energy planning of the heating sector and the implications of both district heating and energy-saving measures, through the optimisation of the complete Italian energy system.

1.2. Scope of the Work and Outline

The aim of the present work is to analyse the impact of both district heating deployment and energy-saving measures in the planning of a decarbonised energy sector in Italy by 2050. The analysis has a particular focus on identifying the technical and economic implications of different levels of strategy implementation, integrating them into a long-term optimisation model of the national energy system.

Therefore, some scenarios combining different levels of DH grid deployment and different levels of energy-saving measures have been implemented in the H2RES software, in order to analyse how these scenarios influence the optimisation of the entire energy system. Consequently, the impact of DH expansion and the implementation of energy-saving solutions are not analysed in isolation; rather, they are assessed in terms of their mutual effects and influences on the entire energy system.

The novelty of this paper lies in this aspect. Indeed, the energy planning of the heating sector decarbonisation is analysed in the context of the transition of the national energy system towards zero-carbon emissions. This is achieved through the use of a long-term optimisation model with a perfect foresight approach, which includes numerous power-to-x technologies and energy storage solutions. In this way, the analysis of the heating sector is not isolated from the system but is integrated into the optimisation of the transition of the entire national energy system. Therefore, the decision variables related to the heating sector are linked and influenced by the transition of the national energy system.

In Section 2, the materials and methods employed in the present study are delineated. In detail, in Section 2.1, the H2RES model is presented; Section 2.2 describes the heating sector in Italy; Section 2.3 defines the scenarios for the district heating deployment and the energy-saving measures implementation; finally, Section 2.4 summarises the technical and economic assumptions.

Section 3 presents and discusses the results of the present study. In detail, the outcomes of the reference scenario are presented in Section 3.1. Furthermore, Section 3.2 presents a comparison between the different heating decarbonisation scenarios.

Finally, in Section 4, the principal findings of the present study are summarised and concluding remarks are provided.

2. Materials and Methods

The objective of this paper is to analyse the impact of different levels of implementation of both district heating and energy-saving measures on the heating sector and, more generally, on the decarbonisation process of the entire Italian energy system.

In order to achieve this, two scenarios for the development of district heating (DH) and two scenarios for the implementation of energy-saving measures have been proposed.

In detail, DH development concerns the deployment of the fourth-generation DH network and the installation of DH substations to supply the heating demand. Energy-saving measures only involve passive energy efficiency measures regarding the building retrofit, such as insulation or window replacement, and more description is provided in Section 2.3.

Through the combination of these levels, four scenarios have been analysed. Furthermore, a reference scenario, taking into consideration the average implementation levels, has been simulated in order to analyse the entire transition process and to compare the alternative scenarios.

These scenarios have been then simulated by means of the H2RES software. Therefore, the level of DH deployment and the implementation of passive energy-saving measures are factors exogenous to the model, whereas the typology, capacity and installation time of heating systems are endogenous variables decided internally on the model. The model, at the same time, allows for the optimisation of the complete decarbonisation process of the energy system up to 2050 in 5-year steps. In this way, the decision variables related to the heating sector are linked and influenced by the transition of the entire energy system.

2.1. H2RES Model

H2RES is a long-term energy modelling tool that employs a model based on long-term linear optimisation [28,33]. This model combines sector coupling solutions with high temporal resolution, operating on an hourly basis, encompassing several technologies.

Its main objective is to optimise capacity investments in the different energy sectors, technology operation and storage levels.

One of the principal characteristics of this software is its comprehensive consideration of the interactions between the various energy sectors, which include power, heat, industry and transport. This holistic approach enables H2RES to provide a detailed description of the dynamics inherent in each sector and the interdependencies between them in future renewable energy systems.

The optimisation approach used by the H2RES software is perfect foresight; therefore, the model develops a single optimisation problem, considering all simulation steps together and the system in its wholeness.

In Figure 1, a graphical representation of the H2RES software is provided.

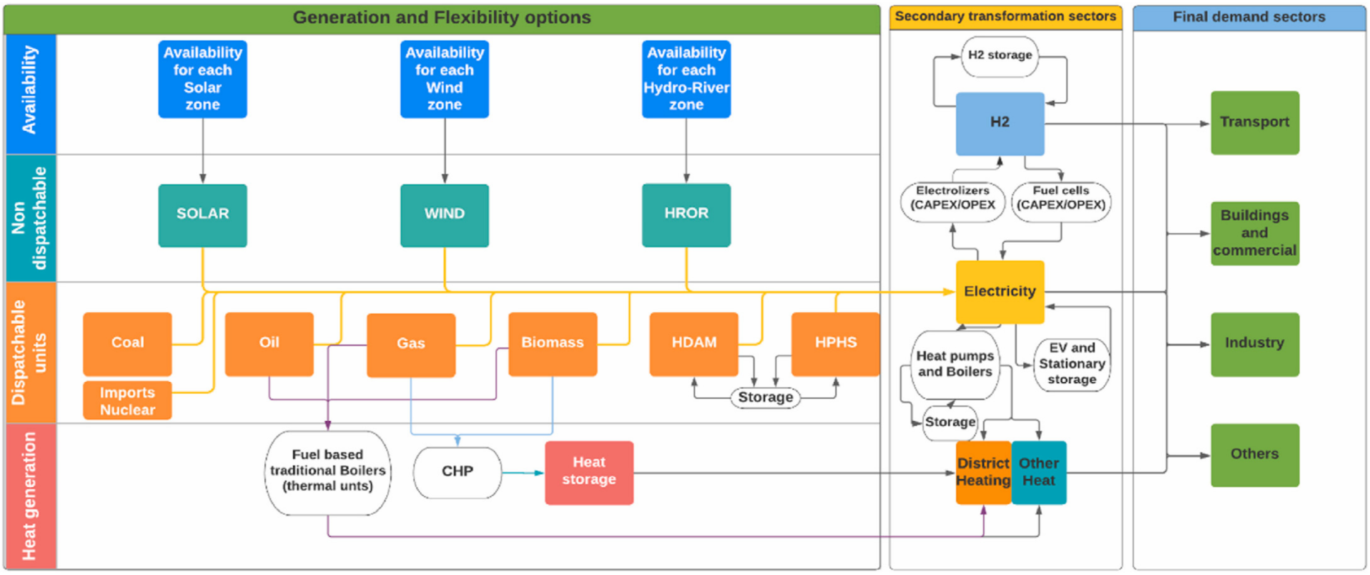

Figure 1. H2RES software.

H2RES encompasses a diverse array of technologies, encompassing conventional power generators and renewable energy sources such as solar, wind (both on-shore and off-shore), and hydropower. Furthermore, users are afforded the opportunity to delineate time profiles, capital costs, and initial capacity levels for each technology.

The model treats the heating sector in a comprehensive manner, encompassing both centralised (e.g., district heating) and decentralised generation. It incorporates a range of heat generation options, including fossil fuel boilers, biomass boilers and heat pumps (HP). This extends to the analysis of power-to-X technologies, facilitating the investigation of varying technical characteristics, capacity potentials and cost structures.

The decision variables within H2RES relate primarily to the capacity of the technologies. The model assigns annual investment capacities to each technology, considering the decommissioning of end-of-life plants. Then, the tool optimises the variables representing the output of generators and storage for each hour of each simulated year, identifying the lowest cost configuration. Finally, it manages the energy storage levels for each technology.

The mathematical representation of the optimisation objective of the H2RES software is shown in Equation (1).

$$\sum_{y}\sum_{p}\sum_{t} df_{y}\left[vC_{t,p,y}D_{t,p,y} + C_{t,y}K_{t}Inv_{t,y} + R_{t,p,y}Ramp_{t,p,y} + I_{p,y}Imp_{p,y} + CO_2Price_{y}CO_2Levels_{t,p,y}\right] \quad (1)$$

Equation (1) models the dispatched energy (D) for each technology (t) by hour (p) and year (y). Variable costs (vC) are derived from both fuel and non-fuel expenses (Equation (2)).

$$vC_{t,p,y} = \left[\frac{FuelCost_{t,p,y}}{eff_{t,p,y}} + NonFuelCost_{t,p,y}\right] \quad (2)$$

Annualised capital costs (K_t) are based on the invested capacity ($Inv_{t,y}$) and capital costs ($C_{t,y}$), which can vary over time. The costs of ramping operations up or down and importing electricity are also considered (third and fourth term of Equation (1)). Additionally, CO_2 emission costs are included.

The overarching objective of the H2RES model is to minimise annual operating and capacity costs over the entire planning horizon, employing a perfect foresight approach.

This necessitates a meticulous examination of the various cost elements, including dispatch costs, annualised capital costs, ramping costs, import costs and costs per unit of CO_2 emissions.

Furthermore, the H2RES model imposes several constraints with regard to the disaggregation of demand levels between sectors, the setting of maximum limits on technological production based on installed capacity, the consideration of technical constraints and the management of storage charge status. In addition, the model allows the user to choose additional policy constraints, such as maximum CEEP (critical excess electricity production) levels, renewable energy penetration targets and annual limits on CO_2 emission levels. A further constraint concerns the overall consumption of biomass in order to ensure its sustainable exploitation.

2.2. Heating Sector in Italy

The H2RES model of the Italian energy system has been previously employed in other research works, and the input data are described in detail in Ref. [34].

The heating sector in Italy is mostly dominated by natural gas boilers. Italy is a country with a significant reliance on natural gas, with the majority of its electrical and thermal energy being produced from this source. Furthermore, the development of district heating in Italy has been constrained by the availability of a capillary gas network, with only 3.5% of the total heating demand in Italy being supplied by district heating.

In Figure 2, the current individual and district heating demand in Italy is depicted according to the technology employed.

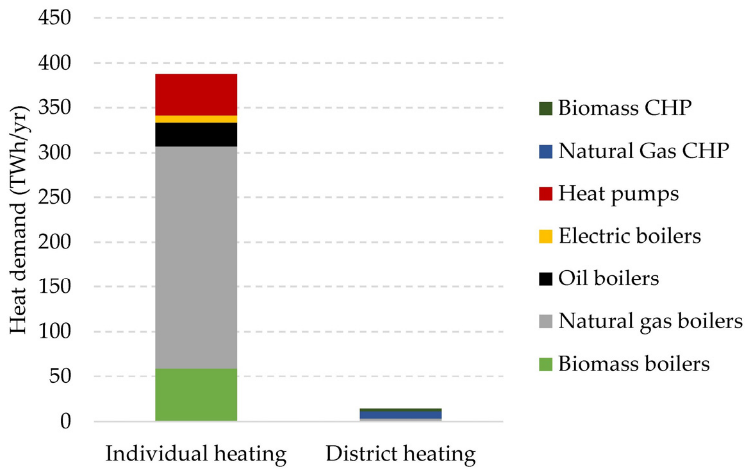

Figure 2. Current individual and district heating demand in Italy by fuel.

2.3. District Heating Deployment and Energy-Saving Scenarios

DH deployment is one of the main actions taken to decarbonise the building stock in urban areas [18]. Within the Heat Roadmap Project, the maximum Italian DH potential was set at 60% [35]. Furthermore, the project enabled the development of a cost function for the development of the DH network in Italy, based on a detailed cost analysis by population density.

Two district heating penetration scenarios have been developed. In the first scenario (Low DH), a conservative approach has been adopted, with the assumption that district heating would only cover 20% of the heat demand in buildings in Italy by 2050. In contrast, the High DH scenario assumes a strategy for the decarbonisation of the building stock that is highly reliant on district heating, with a grid diffusion that would result in 50% of the heat demand being met by centralised production by 2050.

Finally, the reference scenario considers an average value between the two developed scenarios.

Two further scenarios have been developed regarding the implementation of energy-saving measures for the building stock. In accordance with Ref. [36], an optimal level of energy savings for Italy has been estimated to be approximately a 30% reduction in heating demand. Moreover, a cost curve pertaining exclusively to passive measures, such as insulation or window replacement, has been developed for Italy.

The Low ES scenario concerns the implementation of energy-saving measures with the objective of achieving a 20% reduction in demand by 2050. Conversely, the High DH scenario entails a 40% reduction in heat demand in the building stock by 2050. The reference scenario assumes an average value of 30% for the same target year.

A summary of the targets set for 2050 in the developed scenarios is provided in Table 1. The achievement of the different targets is contingent upon a linear increase in the values in each scenario.

Table 1. District heating deployment and implementation of energy-saving measures in the proposed decarbonisation scenarios of the heating sector.

Scenario	Share of Heat Demand Supplied by District Heating by 2050	Heat Demand Reduction by Means of Energy-Saving Measures by 2050
Reference	35%	30%
Low ES/Low DH	20%	20%
Low ES/High DH	50%	20%
High ES/Low DH	20%	40%
High ES/High DH	50%	40%

2.4. Technical and Economic Assumptions

The main technical–economic assumptions employed in this study are presented in Table 2. Furthermore, Table 3 illustrates the maximum installable power for photovoltaic (PV), onshore and offshore wind in accordance with Ref. [37]. The energy demand profiles of the various energy carriers in the different energy sectors have been considered in accordance with previous work [38] and the model developed in Ref. [34].

In order to consider non-linear functions that can describe the variation of costs associated with the implementation of the DH network and energy-saving measures, dedicated cost curves have been considered [39].

In detail, DH development concerns the deployment of the fourth-generation DH network and the installation of DH substations to supply the heating demand. Energy-saving measures only involve passive energy efficiency measures regarding the building retrofit, such as insulation or window replacement.

In Ref. [35], a cost curve for DH grid has been developed, taking into account climatic region, population density and the constraints of urban planning and the built environment. Such a curve has previously been employed in other research and is illustrated in Figure 3. Moreover, the cost of DH substations has been considered in accordance with Ref. [40].

In order to assess the costs of energy savings, the cost curve of energy efficiency measures for the Italian building stock, developed in the context of the Heat Roadmap Europe, has been considered [36,41]. The curve is depicted in Figure 4.

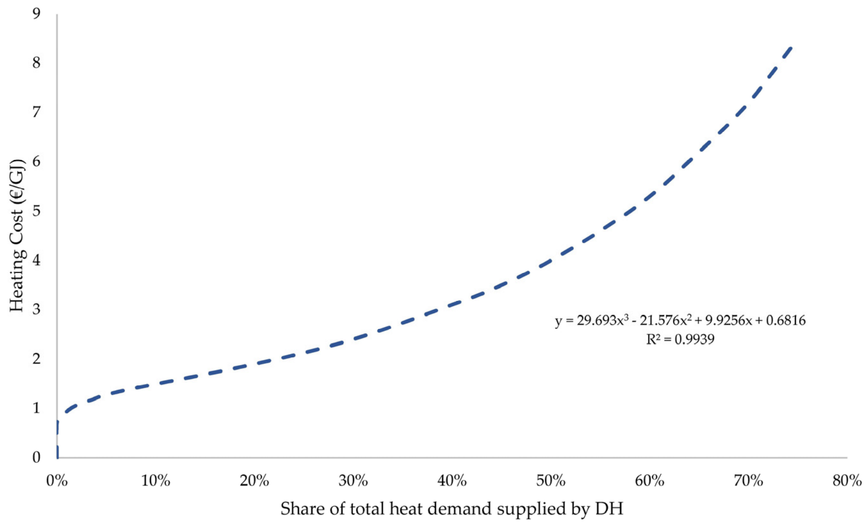

Figure 3. Distribution cost of heating at percentage share of total heat market for Italy [39].

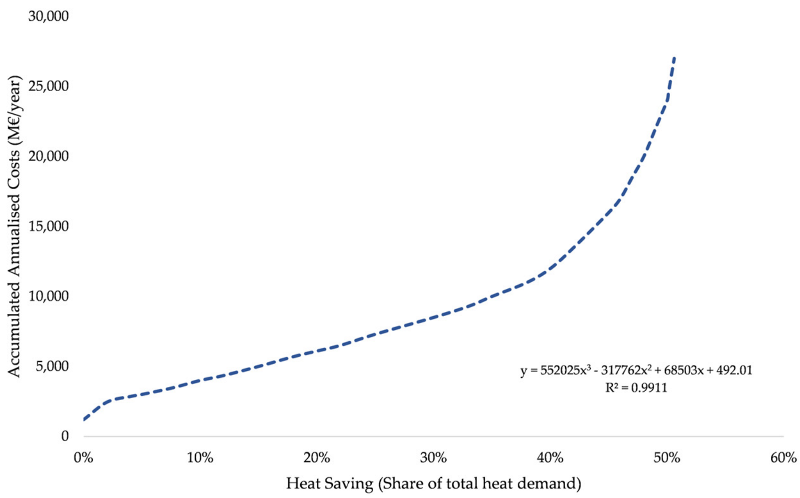

Figure 4. Cumulated annualised costs for heat savings in Italy [39].

Table 2. Main input data for the H2RES model of the Italian energy system.

Technology	Units	INV 2020 (M€/Unit)	INV 2030 (M€/Unit)	INV 2040 (M€/Unit)	INV 2050 (M€/Unit)	Efficiency/Full Load Hours	Refs.
PV	MW	0.92	0.58	0.42	0.33	1517	[42,43]
On-shore Wind	MW	1.79	1.07	0.92	0.86	2418	[42,44]
Off-shore Wind	MW	3.22	1.93	1.66	1.59	2759	[42,44]
PEMFC CHP	MW	1.3	1.1	0.9	0.8	50%	[45]
SOFC CHP	MW	3.3	2	1.3	0.8	60%	[45]
Alkaline Electrolyser	MW	0.65	0.45	0.3	0.25	66.5–78	[45]
SOEC Electrolyser	MW	4.5	1.9	1.3	0.78	77–83.5%	[45]
PEM Electrolyser	MW	0.92	0.65	0.45	0.4	58–70.5%	[45]
H2 Storage (tanks)	MWh	0.057	0.045	0.027	0.021	-	[45]
Biomass Boiler	MWth	0.47	0.447	0.425	0.404	79–85%	[45]
Gas Boiler	MWth	0.278	0.265	0.252	0.24	90%	[45]
Centralised HPs	MWth	1.2	1.07	1.02	0.96	3.3 (SCOP evaluated)	[45]
Individual HPs	MWth	1.56	1.32	1.22	1.13	3.1 (SCOP evaluated)	[45]
Geothermal HP	MWth	1.932	1.836	1.74	1.566	4.6 (SCOP evaluated)	[45]
Electric Boilers	MWth	0.89	0.85	0.81	0.77	100%	[45]

Table 3. Variable RES (VRES) capacity installation potential in Italy [37,46].

RES	Capacity Potential (GW)
PV	357.4
On-shore Wind	115.4
Off-shore Wind	55.7

3. Results and Discussion

The energy system's decarbonisation has been firstly implemented in the reference scenario. Outcomes are shown and discussed in Section 3.1. Furthermore, in Section 3.2, the comparison between the different heating decarbonisation scenarios is presented.

3.1. Reference Scenario

In the reference scenario, energy-saving measures are implemented with the objective of reducing the heating demand in buildings by 30% by 2050. Furthermore, DH is projected to account for 35% of the total heat demand by 2050.

A simulation has been conducted to assess the potential for the complete decarbonisation of the Italian energy system in the reference scenario.

Figure 5 depicts the projected evolution of electricity generation by fuel in the reference scenario—from the present to 2050. Furthermore, Figures 6 and 7 illustrate the evolution of individual heating and district heating demand, respectively, disaggregated by fuel, until 2050.

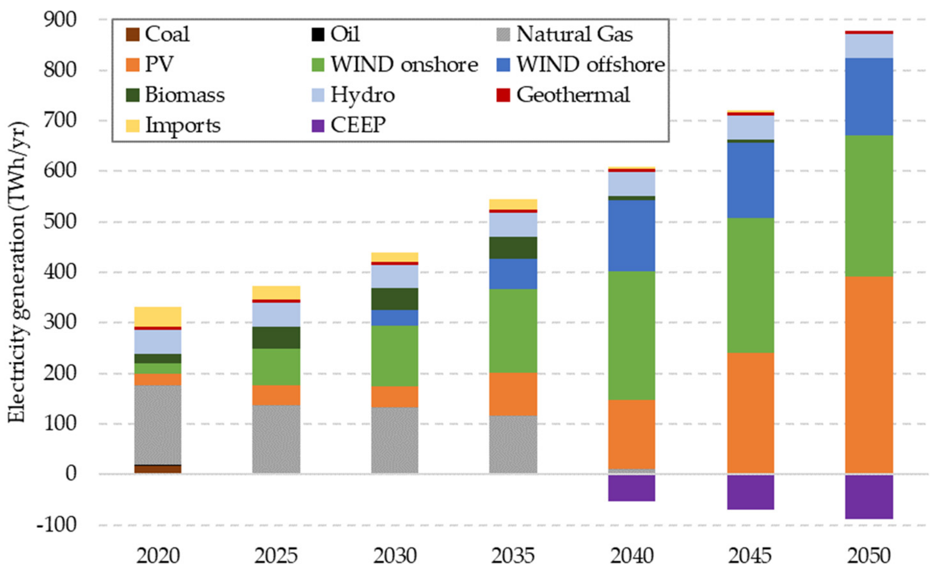

Figure 5. Electricity generation by fuel for the reference scenario.

The maximum potential of installable wind power capacity is a constraint on the optimal configuration of the energy system. In fact, such wind availability is fully utilised for both onshore and offshore wind. As early as 2040, electricity generation from natural gas is minimised, increasing the share of renewables in electricity generation to almost 100%. By 2050, biomass is no longer used for electricity generation and only hydro and geothermal energy are used as dispatchable generation, reaching a variable RES share (VRES) of 94%. In addition, the critical excess electricity production is around 10% of generation.

Individual heating is already fully electrified by 2035. Indeed, the deployment of heat pumps starts in the first simulation steps. By 2050, the demand for individual heating is halved, both because of the overall reduction due to energy-saving measures and because of the shift from individual to centralised heat production.

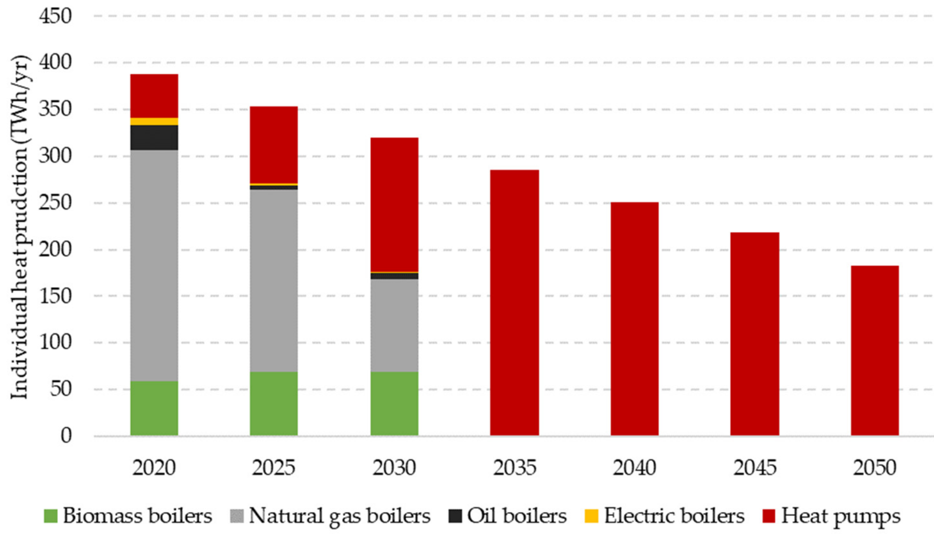

Figure 6. Individual heating by fuel for the reference scenario.

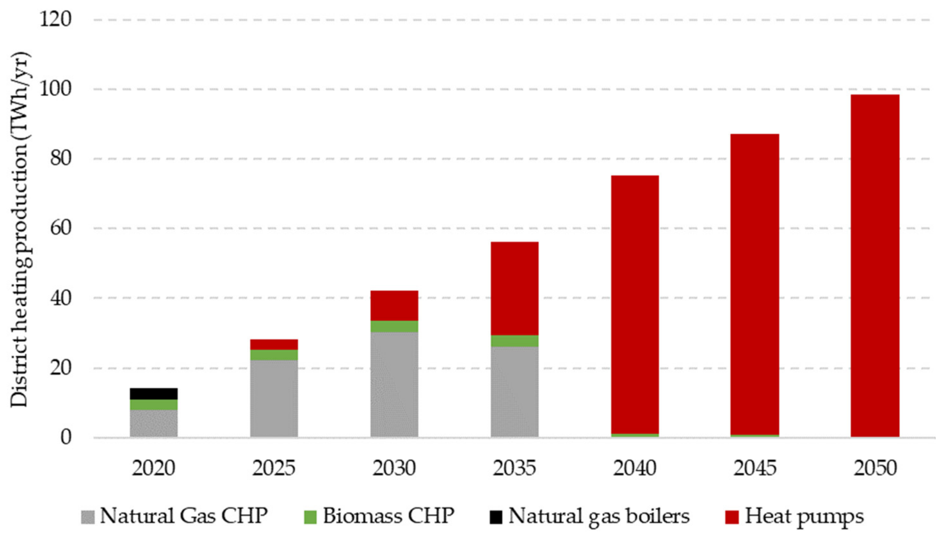

Figure 7. District heating by fuel for the reference scenario.

The expansion of district heating is linked to a significant increase in heat pumps to reach full electrification by 2050.

In 2035, most of the heat demand is supplied by heat pumps and in 2040, almost complete electrification is achieved, with a small residual share of biomass. Therefore, as early as 2040, it is possible to achieve the full decarbonisation of the sector in an efficient and economic manner.

By 2050, biomass is not present in either electricity or low-temperature heat production. Solar thermal is not included in the energy modelling tool. Its inclusion and the analysis of the role of this technology can represent a future development of this work.

3.2. Comparison of Different Scenarios

Four further scenarios combining the different levels of DH and energy-saving measures have been simulated.

In Figure 8, the individual and district heating production by 2050 in the different scenarios are depicted. Furthermore, in Figure 9, the electricity generation by 2050 in the different scenarios is depicted.

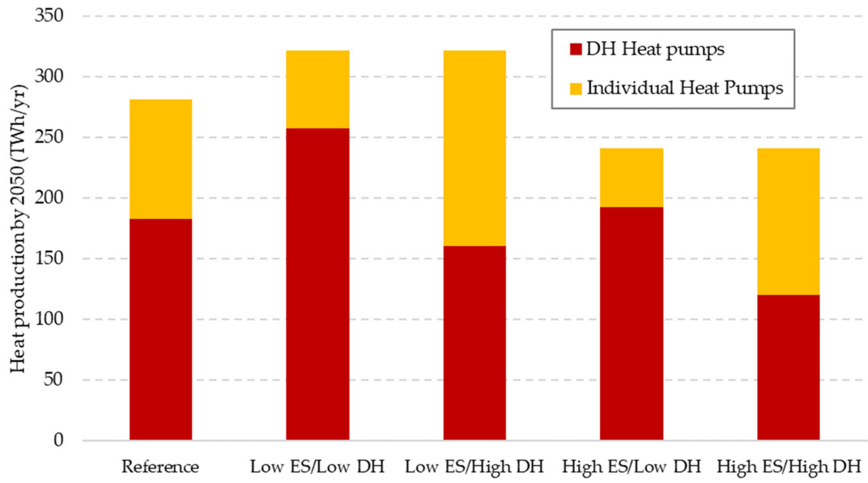

Figure 8. Individual and district heating production by 2050 in the different scenarios.

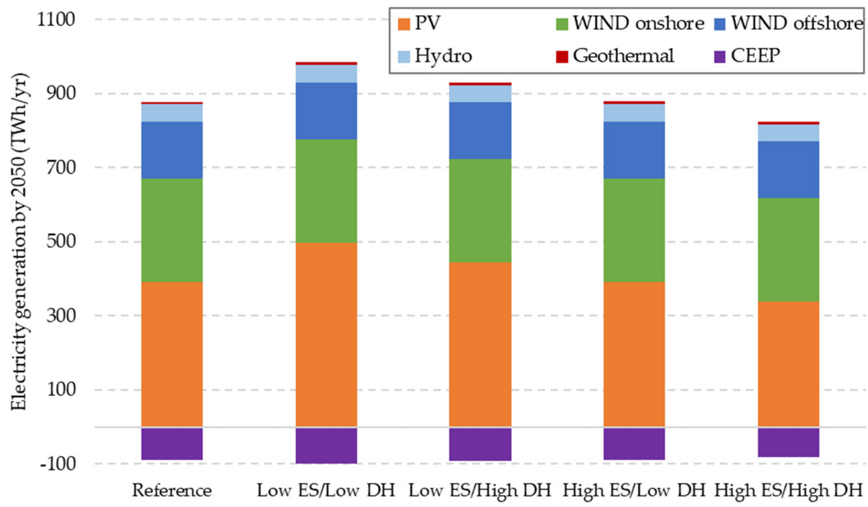

Figure 9. Electricity generation by 2050 in the different scenarios.

Individual heat production in 2050 varies considerably between scenarios, ranging from 120 to 257 TWh/year. Similarly, the heat demand provided by district heating varies considerably, from a minimum of 48 TWh/year to 161 TWh/year.

In all scenarios, the only technological solution to meet the heat demand in the residential sector is always either centralised or decentralised heat pumps. Indeed, such a system provides low-temperature heat in an efficient and cost-effective way and is the preferred solution in all scenarios.

The Low ES scenarios are characterised by an increase in both heat and electricity production. However, this increase differs depending on the DH scenario considered. Indeed, a large share of centralised generation allows the system to operate more flexibly and efficiently, with greater use of thermal storage to integrate VRES generation.

The development of fourth-generation DH allows for a greater integration of non-dispatchable electricity generation and increased system flexibility. Indeed, the increase in DH penetration is correlated with a reduction in overall electricity generation. This makes it possible to reduce the installed PV capacity and CEEP level of the system.

In addition, the different scenarios were also compared in economic terms, assessing both the overall investment over the period and the annual costs to 2050 of the building heating sector.

In Figure 10, the overall investments in the heating systems and infrastructure in the different scenarios are depicted. Furthermore, Figure 11 shows the annual costs by 2050 of building heating sector in the different scenarios.

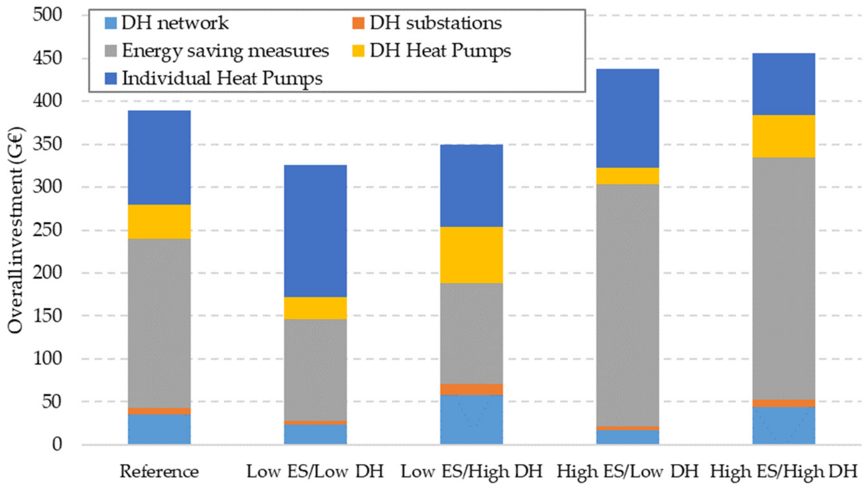

Figure 10. Overall investments in the heating systems and infrastructure in the different scenarios.

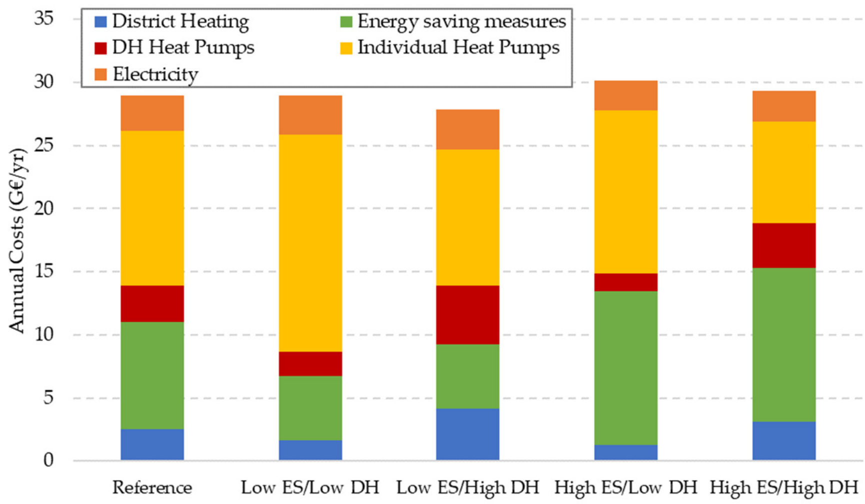

Figure 11. Annual costs of heating sector by 2050 in the different scenarios.

Energy-saving measures account for the largest share of total investments in almost all scenarios. Only in the Low ES scenarios do total investments in heat pumps exceed those in energy efficiency. This shows that passive building interventions are extremely expensive. However, they have an extremely long investment life and lead to a drastic reduction in thermal energy demand in buildings. In fact, the share of these measures in the annual system costs to 2050 is lower than their share in the total investment over the period.

The investment required to develop the DH network is extremely small compared to the other items. DH also accounts for a relatively small proportion of annual system costs. However, this increase in cost is offset by the reduction in the cost of heat pumps from individual systems to centralised systems, which are characterised by larger sizes and lower specific investment costs.

The complete decarbonisation of the building heating sector requires an investment plan of between EUR 300 and 420 G over the whole period considered, i.e., about 30 years.

These investments are reflected in most of the annual costs. Indeed, these costs in 2050 are mainly composed of the annualisation of investments in the different measures and operation and maintenance costs. The costs related to electricity consumption for heat pumps represent an extremely small share of around 8–11% depending on the scenario.

Low levels of DH are correlated with higher costs compared to the reference scenario, while higher DH penetration reduces annual costs regardless of the energy-savings scenario. On the contrary, an increase in the targets for the reduction of the heat demand through energy-saving measures leads to an increase in both the investment and the annual costs.

The High ES/High DH scenario allows us to reduce the heating demand in buildings and make the heat production more efficient. Such a scenario reduces heat demand and electricity generation compared to the reference scenario by 14% and 6%, respectively, while increasing annual costs by 1.3%. It also makes it possible to ensure a greater integration of renewables by providing flexibility in the energy system.

Developing district heating to its full potential is therefore a priority, even in a country like Italy where full load hours for heating are significantly lower than in many northern European countries. In the best scenario, 40% of the Italian heat demand can be supplied by fourth-generation district heating.

Energy-saving measures offer clear benefits in terms of reducing heat demand and therefore energy production, but at a higher annual cost and with a significant increase in investment. Indeed, energy-saving measures often represent the first item of expenditure, corresponding to a share of total investments varying between 34% and 64%.

Cost analyses are obviously conditioned by the economic assumptions made in this article. However, the trend assumed by the main interventions seems clear, and large variations in investment costs would be necessary to change the qualitative results.

Furthermore, the results of the present work are consistent with the existing literature, which emphasises that DH should be expanded to its maximum potential and that an appropriate level of energy-saving measures should be identified through a trade-off between reducing primary energy and increasing system costs [32,36].

To do this, the use of an optimisation system for the entire national energy model would allow for the impact of the two strategies to be properly evaluated. In a further development of this work, these exogenous variables can be integrated into the model itself in order to identify the optimal implementation level of the strategies.

4. Conclusions

The aim of this work is to assess the impact of district heating expansion and the implementation of energy-saving measures on the decarbonisation of the Italian building stock by 2050, analysing the combined impact, reciprocal effects and technical–economic implications on the entire national energy system.

In order to achieve this, the aforementioned measures have been implemented via the H2RES software in a series of scenarios, each representing a different level of implementation of the measures. This was executed in a long-term optimisation model of the national energy system.

The main findings of the work can be summarised as follows:

- In the proposed scenarios, by 2035, individual heating is fully electrified; by 2040, almost a complete decarbonisation of the electricity and heat sector is achieved.
- Heat pumps emerge as the best and only technology to provide heat at both centralised and decentralised levels in 100% renewable energy systems. As an already commercial and high-performance technology, their growth occurs in the first steps of the simulation.
- The use of biomass is very low in the electricity system and zero in the heating sector by 2050.
- District heating expansion is a priority for the decarbonisation of the building stock, even in a country like Italy where full load hours for heating are significantly lower than in many northern European countries. In the best scenario, 40% of the Italian heat demand can be supplied by fourth-generation district heating.
- The development of fourth-generation district heating to its full potential makes it possible to reduce the costs of the thermal sector, make greater use of thermal

storage and provide high levels of flexibility to the power system, thus facilitating the integration of non-dispatchable renewable generation.
- Energy-saving measures offer clear benefits in terms of reducing heat demand and therefore energy production but at a higher annual cost and with a significant increase in investment. Indeed, energy-saving measures often represent the first item of expenditure, corresponding to a share of total investments varying between 34% and 64%.
- The increase in DH penetration and the reduction of energy-saving measures allow for a reduction in the annual system costs by 4% compared to the reference scenario.
- The High ES/High DH scenario reduces heat demand and electricity generation compared to the reference scenario by 14% and 6%, respectively, while increasing annual costs by 1.3%.
- The complete decarbonisation of the building heating system in Italy requires an estimated investment of between EUR 300 and 420 G over the next 30 years.

In conclusion, in order to accurately assess the true impact of different measures to decarbonise the building stock, it is essential to consider the different strategies in combination, taking into account the mutual effects and implications on the entire energy system.

The findings of this study underscore the pivotal role of district heating and heat pumps in both decarbonising the district heating supply and integrating greater shares of non-dispatchable renewables. Furthermore, the necessity of energy-saving measures is affirmed, recognising the need to identify the optimal level of implementation to avoid undue increases in energy system costs.

Finally, this work can provide guidelines for the decarbonisation of the building heating sector, both for the development of national energy plans and for the planning of investment and incentive schemes. Indeed, the results of the study indicate that the deployment of heat pumps should be incentivised immediately, and that support for gas-based technologies, such as condensing boilers, should be discontinued as soon as possible. This is necessary to avoid delaying the decarbonisation of the sector and to prevent the risk of wasting investments by generating stranded assets in the gas infrastructure.

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Nomenclature

ACs	Annual xosts
CEEP	Critical excess electricity production
CO_2	Carbon dioxide
DH	District heating
ES	Energy saving
HPs	Heat pumps
PV	Photovoltaic
RES	Renewable energy sources
VRES	Variable RES

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