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How national decarbonisation scenarios can affect building refurbishment strategies

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A R T I C L E I N F O

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A B S T R A C T

Energy transition is radically changing national energy systems. Nevertheless, the dynamics of this transformation are not considered by end-users in the design of building systems. The present work aims at assessing how the renewable share increase, in both electricity and gas grids, can affect building energy performance. To do this, building energy performance indicators, taking into account growing renewable shares, have been proposed. Four national decarbonisation scenarios have been considered. In a case-study in Italy, conventional boilers, heat pumps, combined heat and power plants and hybrid systems have been analysed. Heat pumps turn out to be the best option if the renewable penetration in the power grid is higher than 40%. The substitute natural gas deployment can increase the competitiveness of cogeneration systems, but not enough to represent the best configuration. National decarbonisation scenarios significantly affect the primary energy and emissions savings of building refurbishment strategies. Conventional indicators, taking primary energy factors as fixed, lead to correct assessment for the reference year, but are unable to describe the actual building energy performance over the system lifetime. Depending on the scenario, the average specific primary energy consumption ranges in 17% and 55% lower than the one assessed with conventional analyses.

1. Introduction

The decarbonisation of energy systems is crucial to mitigate potential damage to ecosystems and people due to human-induced climate change [1].

The urgency of reducing greenhouse gas emissions is speeding up the deployment of renewable energy sources (RES) [2]. RES penetration in the electricity grid is already very high in several countries and will increase everywhere in the coming years [3]. However, the RES deployment will require numerous balancing systems along with the implementation of both short and long-term energy storage systems [4].

The gas grid decarbonisation by means of Substitute Natural Gases (SNGs) is partially linked to the deployment of long-term energy storage technologies for balancing the power grid [5]. Indeed, the chemical conversion of renewable electricity into hydrogen can be a solution to integrate the RES excess while decarbonising other energy sectors [6].

Among the possible hydrogen uses is the direct injection into the gas grid [7]. Such a solution is already envisaged in several national strategies and is suitable for countries characterised by widespread Natural Gas (NG) networks [8]. The advantage of that strategy is the hydrogen use without the need for a dedicated infrastructure [9]. Indeed, several works demonstrated that hydrogen can be blended up to 15–20% by volume in the gas grid without significant changes in mixture parameters [10]. Moreover, such a solution is desirable in the coming years to speed up the deployment of power-to-gas technologies without waiting for dedicated demand in the transport and industrial sectors [11].

Hydrogen can also be further converted in other alternative fuels [12]. Among these, synthetic methane can be an option for the direct NG replacement in end uses [13]. Different catalytic reactors can be used for producing synthetic methane [14]. Biological methanation is also possible, but is currently a less widespread process [15].

The most developed alternative to NG is currently biomethane from biogas upgrading [16]. Anaerobic digestion is a process for treating different biodegradable wastes that is rapidly spreading around the world [17]. However, biogas must first be purified and upgraded to biomethane to be fed into the gas grid [18].

The current SNG production cost is currently very high [19–21]. However, the energy crisis due to rising NG prices may represent an opportunity to accelerate the alternative fuel deployment [22]. Indeed, the European Union recently released the REPowerEU plan to quickly

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reduce its dependence on NG by relying on hydrogen and biomethane [23].

The SNG deployment and the resulting gas grid decarbonisation can contribute to the emission reduction in the building sector, especially in NG countries, such as the UK, Italy and the US, where more than 50% of households are supplied by gas grids [24]. Furthermore, the building sector needs to strongly stimulate its decarbonisation pathway as it is responsible for an important share of the countries' energy consumption. For instance, buildings in Europe account for 40% and 36% of energy consumption and greenhouse gas emissions, respectively [25].

The analysis of building energy systems is a topic that has been widely discussed in literature over the past decades [26]. There is consensus that the best solution in the long run is the electrification of thermal demand by means of Heat Pumps (HPs) [27]. Many studies have also been carried out on the application of small-scale Combined Heat and Power (CHP) plants [28]. In addition, numerous hybrid and multi-carrier configurations have been analysed in the building sector [29]. Hybrid systems can be generally defined as plants combining two or more energy conversion devices [30]. Often, the combined application of two different plants allows to overcome the limitations and exploit the advantages of each system [31].

However, almost all case studies in literature, when analysing the best system configuration to reduce energy consumption in buildings, do not account for the national energy system evolution. Furthermore, national and European regulations take boundary conditions as fixed, developing indicators that describe the energy performance of buildings for the reference year.

Nevertheless, this is an era of deep transformation and the change in the national energy system affects the primary energy factors and then the energy performance of buildings. Thus, the values of exogenous network parameters over the systems lifetime in buildings must be taken into account.

Therefore, case studies in the literature, as well as analyses of building performance for different national certifications, are often correct for the reference year, but are incorrect when analysed over the system lifetime.

Such an aspect is poorly addressed in literature. Roselli et al. [32] analysed the power grid efficiency variation on the energy and environmental feasibility of polygeneration systems. Their findings show how the primary energy saving provided by CHP systems is strictly correlated to the RES contribution to the power grid.

In Ref. [33], different system configurations for supplying heat in a building have been compared having considered the variability of the primary energy factor related to the electricity grid.

The authors of the present work have previously analysed how the RES share increase in electricity and gas grids can affect the competitiveness of gas-driven CHP plants for distributed generation [34]. Accordingly, in countries characterised by high-RES penetration in the power system, CHPs do not provide energy and emission savings. Greening the gas grid can preserve the competitiveness of those technologies. However, in that work the analysis has been limited to the typical application of CHP plants.

To the best of the authors' knowledge, there is no work analysing the effects of RES penetration on electricity and gas grids on different building refurbishment strategies, comparing the application of HPs, CHPs, and hybrid configurations.

Building energy analyses usually overlook the deep transformation that national energy systems are facing. The rapid deployment of renewable generation and the forthcoming growth of alternative fuels will change the nature of the energy carriers consumed by end-users. This dynamic needs to be taken into account when analysing the long-term effects of different solutions for energy savings in buildings.

The aim of the present work is to assess how variation in exogenous grid parameters affects primary energy and emission savings due to building retrofits. Furthermore, this paper aims to investigate how important it is to take this dynamic into account in scientific studies, as well as in the national certification of buildings, in order not to make erroneous assessments on the choice of the best building system configuration. The main purpose is to propose an approach for calculating the building primary fossil energy consumption as well as CO_2 emissions taking also into account the national energy system transformation.

In this paper, several roadmaps for the RES penetration on the electricity and gas grid have been considered to analyse the impact of different national decarbonisation scenarios on the building stock.

Four decarbonisation scenarios of Italian energy system combining two roadmaps for the electricity and gas grid have been assumed based on the main European and national targets. Heat supply temperature has also been considered. Indeed, many dwellings, especially in all those countries where the gas network is widely diffused, use medium to high temperature radiators as heating emission technology. The temperature level affects both the suitability of applied technologies and consequently the efficiency of the whole building system. Therefore, this paper analyses different strategies in two typical reference buildings supplied at high and low temperature. Four typical building energy system configurations have been assessed: gas boiler, HPs, CHP systems and a hybrid configuration combining HPs and CHPs.

In Section 2, the applied methodology for the investigation and the case study have been presented. In detail, Section 2.1 deals with the development of the main indicators and factors for carrying out energy and environmental analysis. In Section 2.2, the proposed roadmaps for the RES share increase and the national decarbonisation scenarios have been discussed. In Section 2.3, the building model assumed as a reference and the building system configurations have been described. In Section 2.4, equations regulating energy balances for simulation and the main technical and economic assumptions have been presented. Then, Section 3 describes the analysis results and discuss the outcomes. In detail, Section 3.1 deals with the effects of decarbonisation scenarios on building system performance and in Section 3.2 the sensitivity analysis on the system efficiencies have been reported. Finally, in Section 4 the main findings of the present works have been outlined.

2. Material and methods

A methodology for assessing the non-renewable primary energy and emission factors associated to both electricity and gas grid, as a function of the renewable share, has been applied. Based on these factors, an indicator for evaluating the specific average primary energy consumption and CO_2 emissions over the building system useful life has been proposed. Such an indicator is an evolution of the traditional indicator used for performance building analysis.

Two different roadmaps for RES penetration on both electricity and gas grids have been considered. Thereby, four national decarbonisation scenarios have been evaluated.

Four building system configurations have been investigated. As a reference scenario, the conventional gas boiler has been considered. Furthermore, heat pump installation, CHP plants and a hybrid system layout by combining CHP and HP have been investigated.

The different configurations have been applied in two typical reference buildings supplied at high and low temperature. The building systems have hence been simulated by changing the network parameters. Furthermore, the evolution of some energy and environmental indicators in the proposed national decarbonisation scenarios, over the considered period, has been analysed.

Such analysis has been compared with a traditional analysis, taking into account primary energy factors fixed at the reference year.

Finally, a sensitivity analysis by varying the system efficiencies has been carried out.

2.1. Energy and environmental analysis

In Ref. [34] a methodology for calculating non-renewable primary energy and emission factors as a function of RES share on the grids has been developed. Those factors have been proposed for both electricity and gas networks, which depend on the electricity renewable share and the SNG share, respectively. That methodology has been developed by the authors regarding the analysis of combined heat and power systems. In the present work, that methodology has been extended and generalised to the building energy performance analysis. Equations (1)–(6) are based on Ref. [34].

The non-renewable primary energy factor of the electricity grid ($f_{nr,el\ grid}$) relating to year t is dependent on the electricity RES share ($\%RES_{el}$) at the same year and can be computed according to Equation (1).

$$f_{nr,el\ grid,t} = \frac{1 - \%RES_{el,t}}{f_c \bullet \eta_{thel}} \tag{1}$$

Where, η_{thel} is the average efficiency of national thermoelectric plants and f_c is the correction factor for grid losses.

Likewise, the non-renewable primary energy factor of the gas grid ($f_{nr,gas\ grid}$) related to year t, depending on the gas RES share due to the SNGs presence in the gas network ($\%SNG$) at the same year, can be computed according to Equation (2).

$$f_{nr,gas\ grid,t} = (1 - \%SNG_t) \bullet f_{nr,NG} \tag{2}$$

Here, $f_{nr,NG}$ is the non-renewable primary energy factor of natural gas, which also accounts for the grid losses.

Thereby, the primary fossil energy consumption (PFEC) of the building, expressed by MWh/yr, can be computed as follows:

$$PFEC_t = E_{el,t} \bullet f_{nr,el\ grid,t} + E_{gas,t} \bullet f_{nr,gas\ grid,t} \tag{3}$$

Where, E_{el} and E_{gas} are respectively the annual electricity and natural gas consumption of the building.

Likewise, the emission factor of the electric grid ($f_{e,el\ grid}$) can be computed according to Equation (4).

$$f_{e,el\ grid,t} = \frac{\left(1 - \%RES_{el,t}\right) \bullet f_{e,thel}}{f_c} \tag{4}$$

Where $f_{e,thel}$ is the average emission factor of national thermoelectric plants.

In Equation (5), the emission factor of the gas grid is reported ($f_{e,gas\ grid}$).

$$f_{e,gas\ grid,t} = (1 - \%SNG_t) \bullet f_{e,NG} \tag{5}$$

Here, $f_{e,NG}$ is the emission factor of NG.

The annual CO_2 emissions of the building, expressed by ton_{CO2}/yr, can be computed as follows:

$$CO_2 = E_{el,t} \bullet f_{e,el\ grid,t} + E_{gas,t} \bullet f_{e,gas\ grid,t} \tag{6}$$

Specific indicators evaluating average primary energy consumption and CO_2 emissions can be calculated.

The specific non-renewable primary energy consumption (EP_{nr}) relating to year t, expressed by kWh/m^{2}yr, can be calculated according to Equation (7).

$$EP_{nr,t} = \frac{PFEC_t}{A} \tag{7}$$

Where A is the building heating surface.

Likewise, the specific CO_2 emissions (CO_2), expressed by kg_{CO2}/m^{2}yr, can be calculated as follows:

$$CO_{2,t} = \frac{CO_{2,t}}{A} \tag{8}$$

Furthermore, the previous indicators can be evaluated over the useful life of the building energy systems.

The specific average non-renewable primary energy consumption ($\overline{EP_{nr}}$), expressed by kWh/m^{2}yr, can be computed according to Equation (9).

$$\overline{EP_{nr}} = \frac{\sum_t PFEC_t}{t \bullet A} \tag{9}$$

Here, t is the plant lifetime.

Finally, the specific average CO_2 emissions ($\overline{CO_2}$), expressed by kg_{CO2}/m^{2}yr, can be calculated according to Equation (10):

$$\overline{CO_2} = \frac{\sum_t CO_{2,t}}{t \bullet A} \tag{10}$$

The proposed methodology is dependent on some parameters related to the case study. Indeed, factors related to the national energy mix and plant characteristics are included in some of the equations. In the present work, the case study is located in Italy and the parameters of the Italian grids have been considered and summarised in Table 1.

2.2. Decarbonisation roadmaps of electricity and gas grids

Some pathways to decarbonise the national energy system have been hypothesised. The Italian energy system has been considered as a case study. Currently, the Italian RES share on the electricity grid is 38.1% [38]. SNGs are underdeveloped in Italy. Their presence on the gas grid stands at 0.13% and is exclusively due to biomethane [39].

A decarbonisation path for the electricity grid has been developed based on the European FitFor55 plan and decarbonisation targets [40]. Accordingly, $\%RES_{el}$ has been set at 74% and 100% for 2030 and 2040, respectively. A more conservative scenario has been assumed on the basis of the Italian national energy and climate plan (NECP), which has not yet been updated to meet the new ambitious targets [41]. This plan proposed to achieve a $\%RES_{el}$ of 55% and 75% by 2030 and 2040, respectively.

European targets concerning the SNG deployment have been improved with the energy crisis and the release of the REPowerEU plan [23]. Accordingly, the European annual NG consumption should be reduced by about 59 bm^3 by 2030. At the same time, an annual biomethane production target of 35 bm^3 has been proposed, while hydrogen production should reduce NG consumption by additional 27 bm^3. Thus, the SNG share in final gas consumption can be considered equal to 18.2% by 2030. Furthermore, according to Ref. [42], annual biomethane production could grow from 35 bm^3 to 95 bm^3 by 2040. If the penetration of hydrogen and derived fuels increased proportionally, this would lead to a %SNG of 50% by 2040. This pathway has been considered as an optimistic scenario of gas grid decarbonisation. To account for a more conservative roadmap, the targets have been halved for each proposed step.

Therefore, two scenarios for the electricity grid decarbonisation and two scenarios for the gas grid have been assumed. Those scenarios may represent foreseeable ranges in which the parameters may be in the coming years. The variation between the assumed targets has been considered as a linear increase. The targets have been summarised in Table 2. Furthermore, the evolution of $\%RES_{el}$ and %SNG until 2040 have been depicted in Fig. 1.

By combining the two pairs of roadmaps, four national decarbonisation scenarios have been considered. The scenarios have been

Table 1
Technical data assumptions for national grids.

Parameter	Unit	Value	Ref.
η_{thel}	–	0.422	[35]
f_c	–	0.851	[36]
$f_{nr,NG}$	–	1.05	[37]
$f_{e,thel}$	kg_{CO2}/MWh_{el}	493.8	[35]
$f_{e,NG}$	kg_{CO2}/MWh_{th}	201.4	[35]

Table 2
RES share and SNG share on electricity and gas grids.

Reference year	Low RES	High RES	Low SNG	High SNG
2021	38.1%	38.1%	0.13%	0.13%
2030	55%	74%	9%	18%
2040	75%	100%	25%	50%

analysed over a period of 20 years, since it can be taken as a realistic lifetime for the different plants which have been assumed herein [43].

2.3. Case study

A building located in Milan, consisting of twenty flats characterised by 67 m^2 of surface, has been taken as a case study. Electricity demand has been modelled according to Ref. [44], which defines average hourly profiles divided by working, pre-holiday and holiday days for each month. Hourly heating load profile has been considered on the basis of the data provided by the Hotmaps Project [45]. The Hotmaps open data repositories make available aggregated hourly load profile on NUTS 2 level for different energy sectors. Heating demand have been considered equal to 30 kWh/m^{2}yr. Such heating requirement corresponds to a class B building according to the Italian regulation in the climatic zone of Milan.

The climatic zone analysed is characterised by 2404° day and a heating period from mid-October to mid-April.

The choice of an efficient building, which does not need any further passive energy-saving measures, is aimed at focusing the analysis on plant configurations and primary energy consumption.

It should also be highlighted that the chosen case study is only functional to quantify the parameters proposed in the methodology. However, this paper does not analyse the variation in the building energy needs, but only the effect of different plant configurations. Therefore, the choice of a generic building model is functional to generalize the analysis as much as possible, according to the purposes of this article.

The main characteristics and energy demand of the building have been summarised in Table 3.

The building has been considered in two different heat supply temperature conditions. Such assumption affects both the applied technology and efficiency of the whole building system.

Four system configurations have been considered for the analysis.

A) Reference scenario: in Italy, as in NG-based countries, most buildings are currently served by NG boilers. In the high-temperature scenario, traditional boilers have been considered. In the low-temperature scenario, a condensing boiler can be applied instead, increasing the system overall efficiency.
B) HP: In this scenario, the heat demand is completely electrified. In the low-temperature scenario, the efficiency of the heat pump is extremely high. If heat must be supplied at high temperatures, a two-stage heat pump must be used, resulting in a lower COP.
C) CHP: the cogeneration system enables the combined production of heat and power. Micro-CHP plants suitable for building applications are characterised by low electrical and high thermal efficiencies [46]. That issue, combined with the thermal storage use, allows the system to be managed to self-consume both electrical and thermal energy by adapting the plant operation to the building energy demand. Typically, CHPs produce heat at high temperatures. Working at low temperatures, thermal efficiency can be increased by using either an integrated or additional condensing heat exchanger.
D) Hybrid system: the combined application of CHP and HP has been considered. Such system has been analysed in literature, showing how it can be more efficient than the single cogeneration system [47]. Furthermore, in the case of perfect coupling, it allows the electricity generation for an additional heat production, avoiding the issues of contemporaneity with the building's energy demand and increasing the system flexibility [48]. The applications at high and low temperatures require the different technologies mentioned before, thus affecting the system efficiencies.

In Fig. 2, the four energy system configurations which have been analysed in the present work are depicted.

2.4. Energy model and technical assumptions

The energy and environmental performance of energy system configurations has been evaluated by a semi-dynamic model implemented in MATLAB-SIMULINK environment. The different configurations have been simulated by hourly step over an entire year. In detail, the balance equations governing the energy flows have been implemented and a model for each energy scenario has been built. The time dependent

Table 3
Main characteristics and energy demand for each dwelling and the building.

Value	Unit	Dwelling	Building
Surface	m^2	67	1340
Electricity demand	MWh/year	1.91	38.2
Heating demand	MWh/year	2.01	40.2

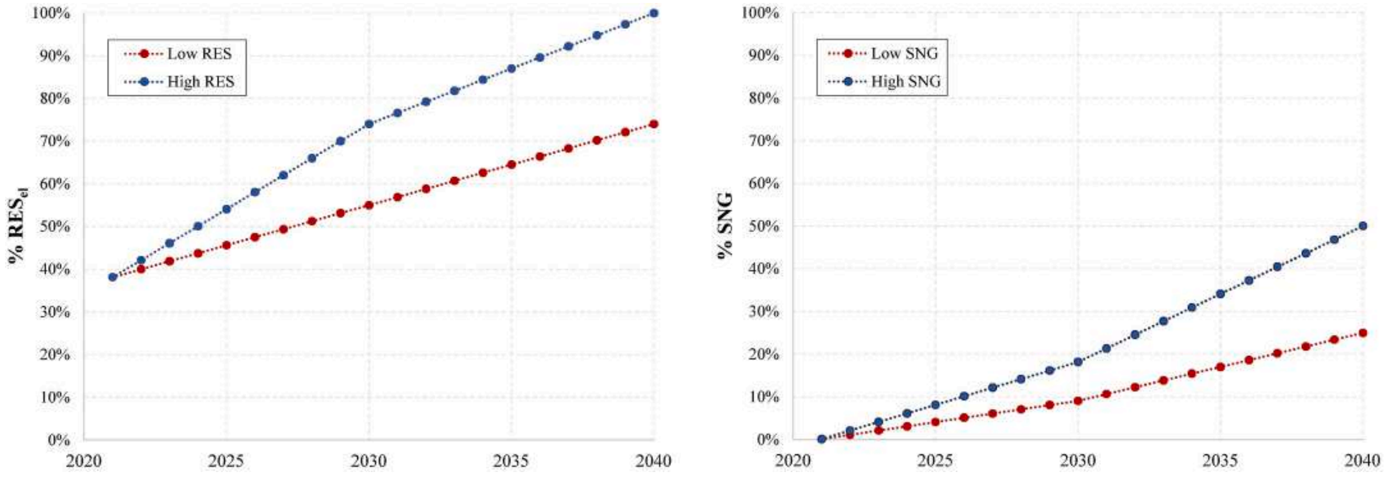

Fig. 1. Roadmaps of electricity and gas grids' decarbonisation.

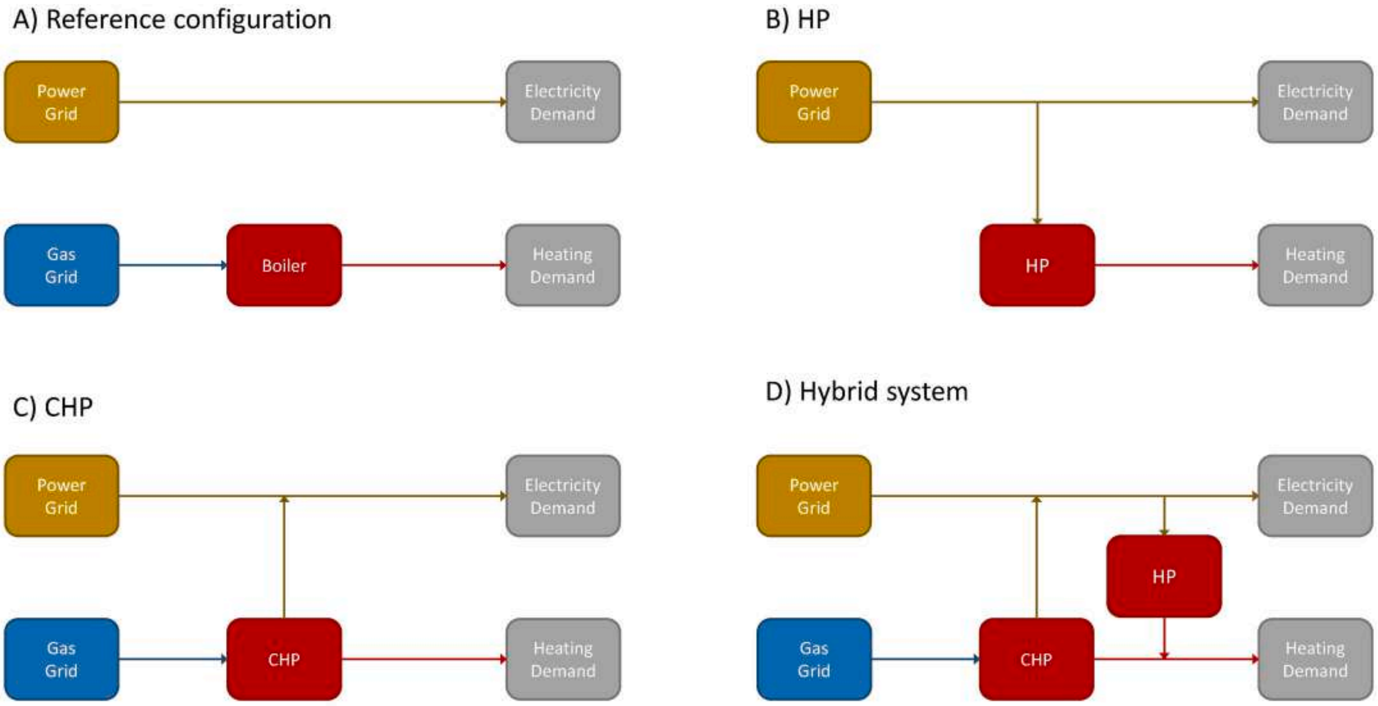

Fig. 2. Block diagram of energy system configurations: A) Reference configuration; B) Heat Pump; C) Combined Heat and Power system; D) Hybrid system.

energy balance equations read as follows:

$$P_{D,el}(t) + P_{HP,el}(t) = P_{GRID,el}(t) + P_{CHP,el}(t) \tag{11}$$

$$P_{D,th}(t) + P_{TES,in}(t) = P_{HP,th}(t) + P_{CHP,th}(t) + P_{Boil,th}(t) + P_{TES,out}(t) \tag{12}$$

$$\frac{P_{CHP,th}(t)}{\eta_{th,CHP}} + \frac{P_{Boil,th}(t)}{\eta_{th,Boil}} + P_{TES,out} = P_{GRID,gas}(t) \tag{13}$$

$$E_{el} = \int_{t_0}^{t} P_{GRID,el}(t) \tag{14}$$

$$E_{gas} = \int_{t_0}^{t} P_{GRID,gas}(t) \tag{15}$$

In detail, Equation (11) represent the energy balance of electricity demand and supply. Equation (12) is the energy balance between heat demand and supply. Equation (13) represents the energy balance for defining the gas grid supply. Finally, Equations (14) and (15) represent the calculation for the annual consumption of electricity and gas, respectively. It is important to point out that depending on the simulated scenario, some terms of those equations must be neglected.

The main technical assumptions regarding the efficiencies of heating systems have been outlined in Table 4. Efficiency and COP parameters have been chosen based on several reports representative of the state of the art of different technologies and considered as average values for the simulation. To discuss the impact of these choices on the results, a sensitivity analysis on the main technical assumptions has been conducted in Section 3.2.

Table 4
Technical assumptions on COP and efficiency of heating systems.

Technology	COP/η	Value	Ref.
Boiler	Efficiency (%)	92%	[49]
Condensing Boiler	Efficiency (%)	102%	[50]
HP	COP	3	[43]
2-stage HP	COP	2	[51]
Micro-CHP	Electrical efficiency (%)	29%	[34]
Micro-CHP	Thermal efficiency (%)	61%	[34]
Micro-CHP	Total efficiency (%)	90%	[34]
Micro-CHP (condensing heat exchanger)	Thermal efficiency (%)	74%	[48]
Micro-CHP (condensing heat exchanger)	Total efficiency (%)	103%	[48]

3. Results and discussion

The system analysis has been conducted in order to identify the annual energy balance associated to the building model. The two reference case studies, the high-temperature (HT) and low-temperature (LT) building, affect the systems behaviour and the annual energy balance. In Figs. 3 and 4, block diagrams of building system configurations with the description of annual energy balances have been depicted in the LT and HT scenario, respectively.

HT configurations have a higher energy consumption due to the lower efficiency of the same systems.

The energy balances do not change as the exogenous parameters vary, while the energy mix consumed from the grid over time changes.

Before dealing with roadmaps, an analysis of energy and environmental indicators, as the RES share in the grids changes, has been developed to initially discuss the impact of grid decarbonisation on choosing the best building system configuration. Three SNG scenarios, characterised by %SNG equal to 0%, 25% and 50%, have been considered.

In Figs. 5 and 6, the PFEC as a function of $\%RES_{el}$ in different SNG scenarios has been depicted for LT and HT configurations, respectively. Furthermore, in Figs. 7 and 8, CO_2 emissions as a function of $\%RES_{el}$ in different SNG scenarios have been shown for LT and HT configurations, respectively.

The results of the analysis show that non-renewable primary energy and CO_2 emissions related to the energy consumption of different plant configurations are highly dependent on the renewable share in both electricity and gas grids.

If there were no renewable energy on the power grid, CHP systems would provide significant energy savings compared to other

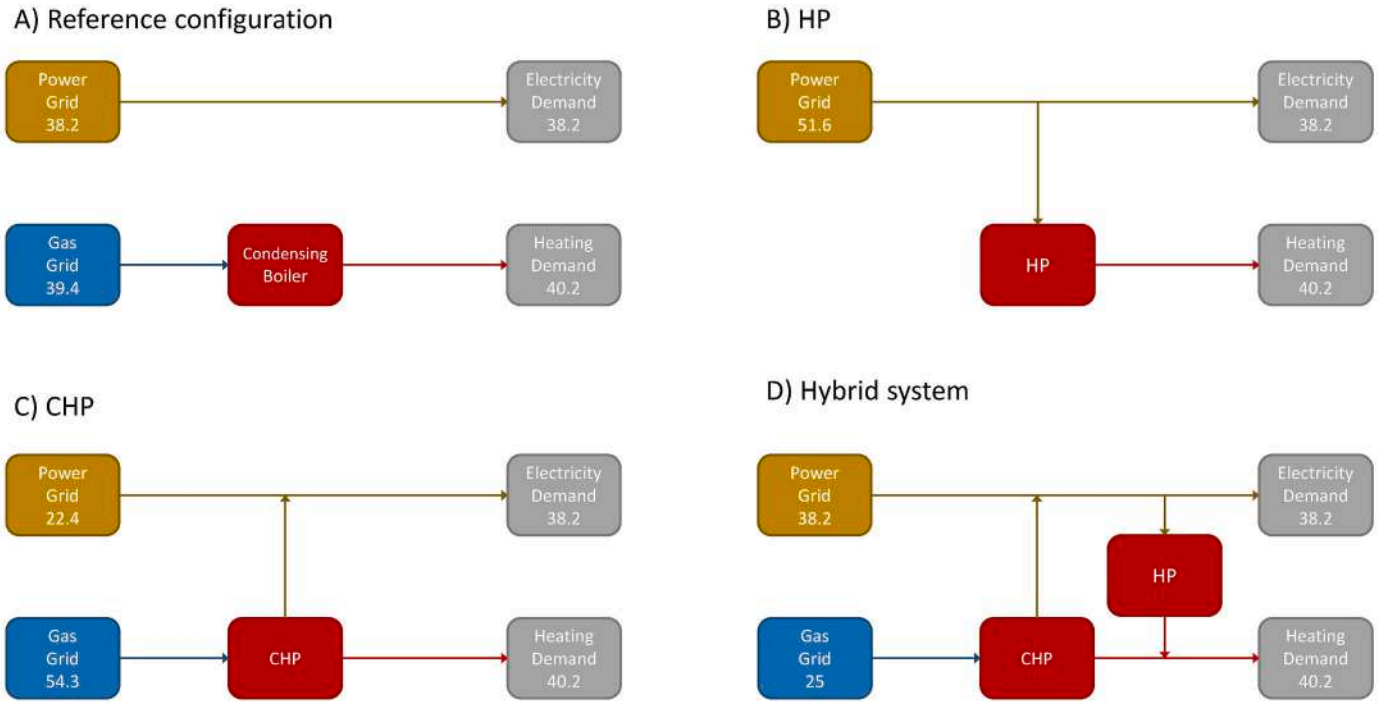

Fig. 3. Block diagram and annual energy balance (MWh/yr) of low temperature building system configurations: A) Reference configuration; B) Heat Pump; C) Combined Heat and Power system; D) Hybrid system.

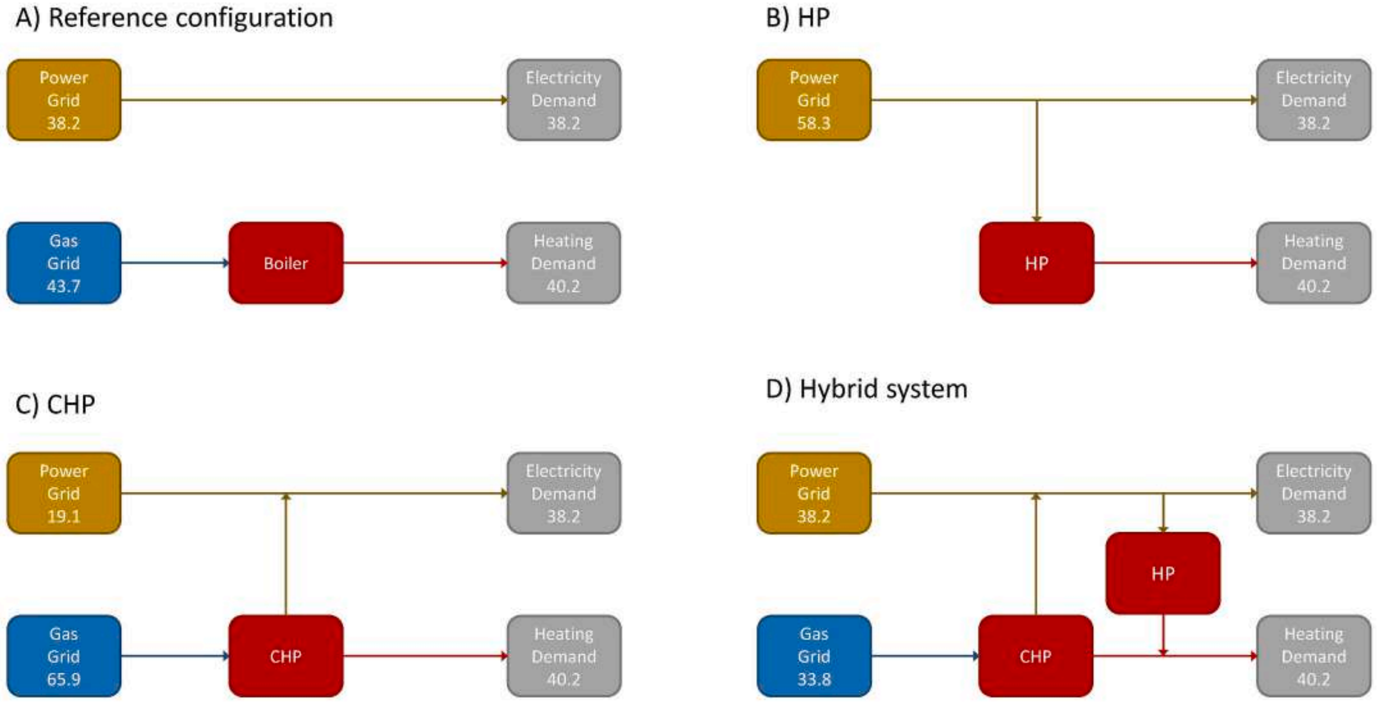

Fig. 4. Block diagram and annual energy balance (MWh/yr) of high temperature building system configurations: A) Reference configuration; B) Heat Pump; C) Combined Heat and Power system; D) Hybrid system.

configurations. However, the competitiveness of those systems worsens sharply as the %RES$_{el}$ increases.

There is a threshold of %RES$_{el}$ for which the heat demand electrification, by means of HPs, turns out to be better than the cogeneration system application. Such a value is extremely dependent on the %SNG on the gas network. Indeed, the gas grid decarbonisation increases that threshold value of %RES$_{el}$. In the 50% SNG scenario, %RES$_{el}$ higher than 60% is required to consider HPs as a better solution than CHP plant installation. Nevertheless, the SNG deployment is partially linked to the electricity RES one. Therefore, it is difficult to envisage a decarbonisation scenario in which SNGs are widely deployed without high-RES penetrations on the electricity grid.

Moreover, without SNGs in the gas grid, the RES share required to make HPs the best option is lower than 40%. That value is achieved by

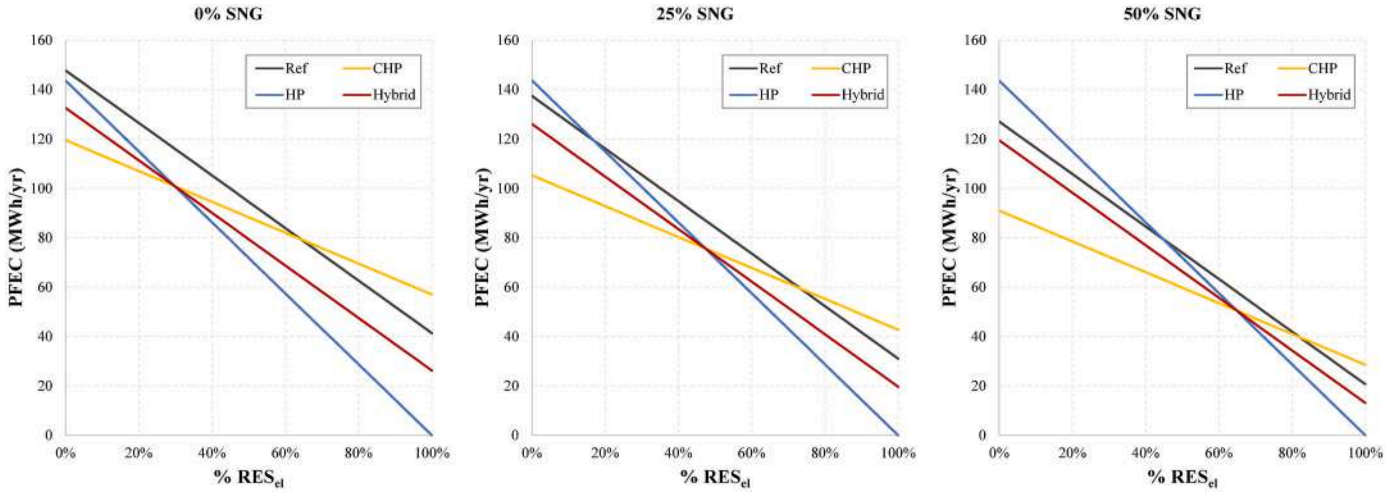

Fig. 5. PFEC as a function of %RES$_{el}$ in different SNG scenarios for Low Temperature configurations.

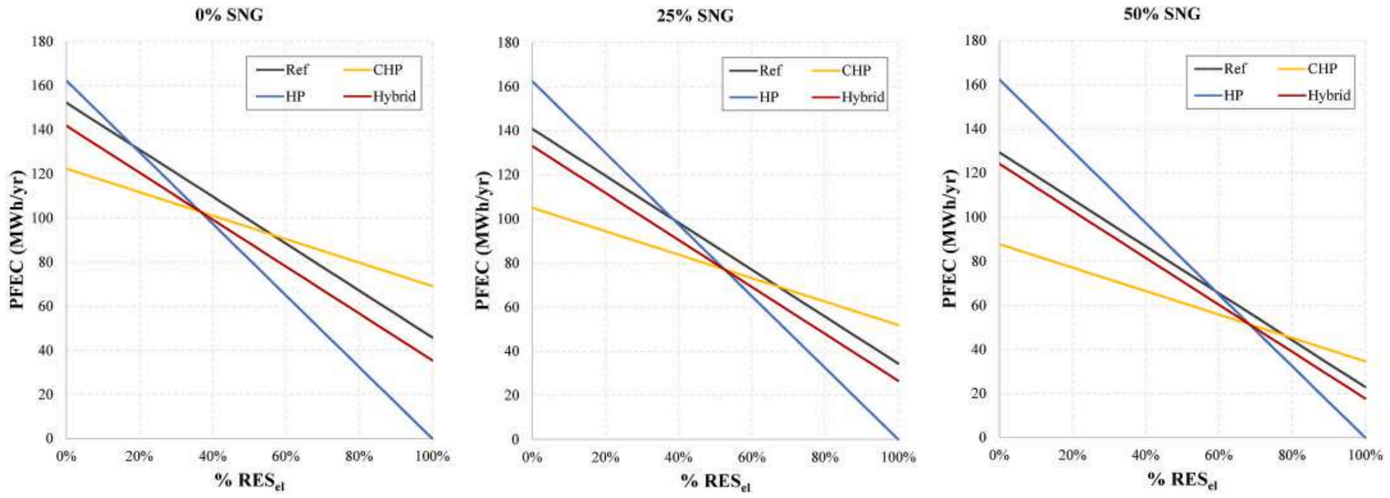

Fig. 6. PFEC as a function of %RES$_{el}$ in different SNG scenarios for High Temperature configurations.

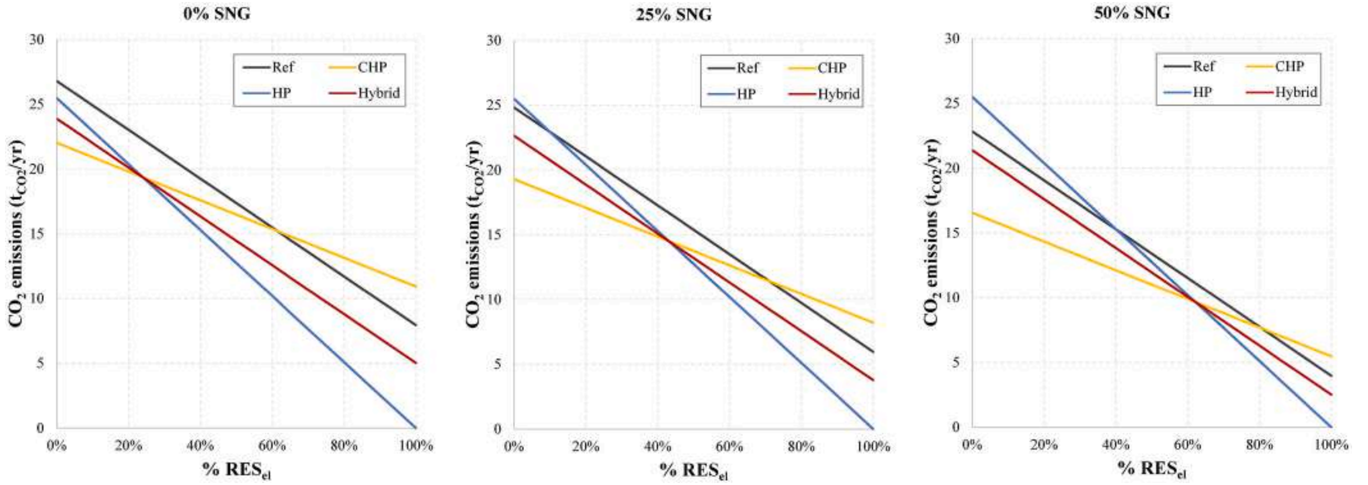

Fig. 7. CO$_2$ emissions as a function of %RES$_{el}$ in different SNG scenarios for Low Temperature configurations.

several countries in the European Union, where the HP installation is already more efficient than micro-cogeneration.

Furthermore, there is a threshold value of %RES$_{el}$ for which CHP systems are correlated with higher energy consumption and CO$_2$ emissions even compared to the reference scenario. This is due to the increase in gas consumption, which results in a lower multiplication factor as the

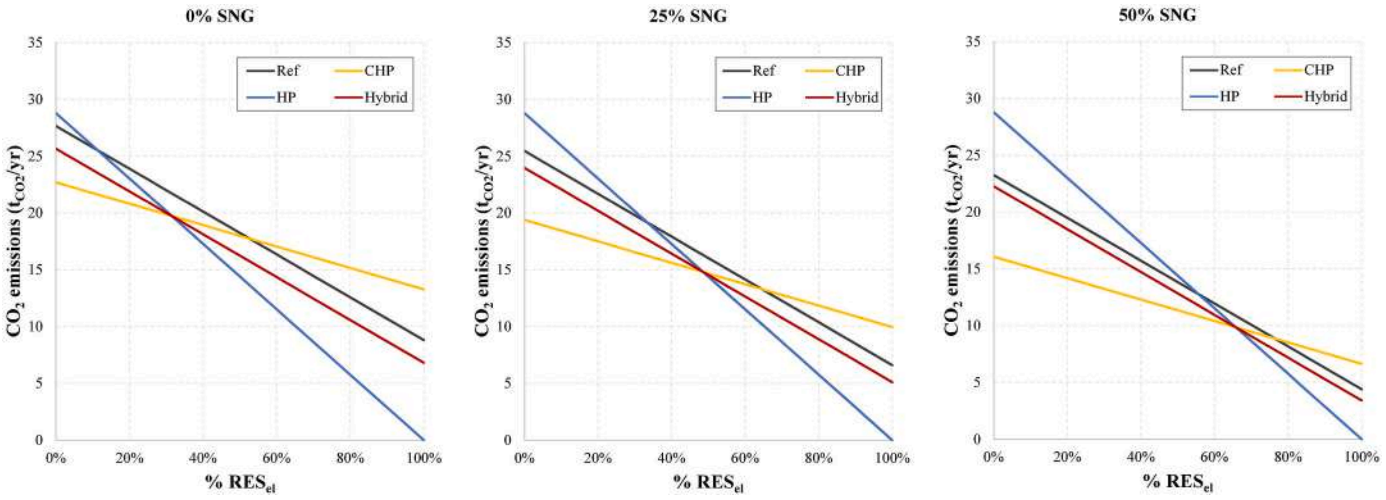

Fig. 8. CO_2 emissions as a function of %RES_{el} in different SNG scenarios for High Temperature configurations.

electricity grid parameters vary.

Hybrid systems turn out to be correlated with lower energy consumption and CO_2 emissions than the reference configuration, whatever the renewable share on the electricity and gas grid. This is due to a more efficient use of gas for the same amount of electricity consumption. Nonetheless, a complete shift to gas or electricity devices is always preferable.

In the HT building scenario, the COP of two-stage HPs is extremely low, and this results in higher competitiveness of CHP systems. Indeed, the threshold values in that configuration are higher than those related to the LT scenario. Nevertheless, the difference between those values is not so impressive and, for high %RES_{el}, HP is always the best

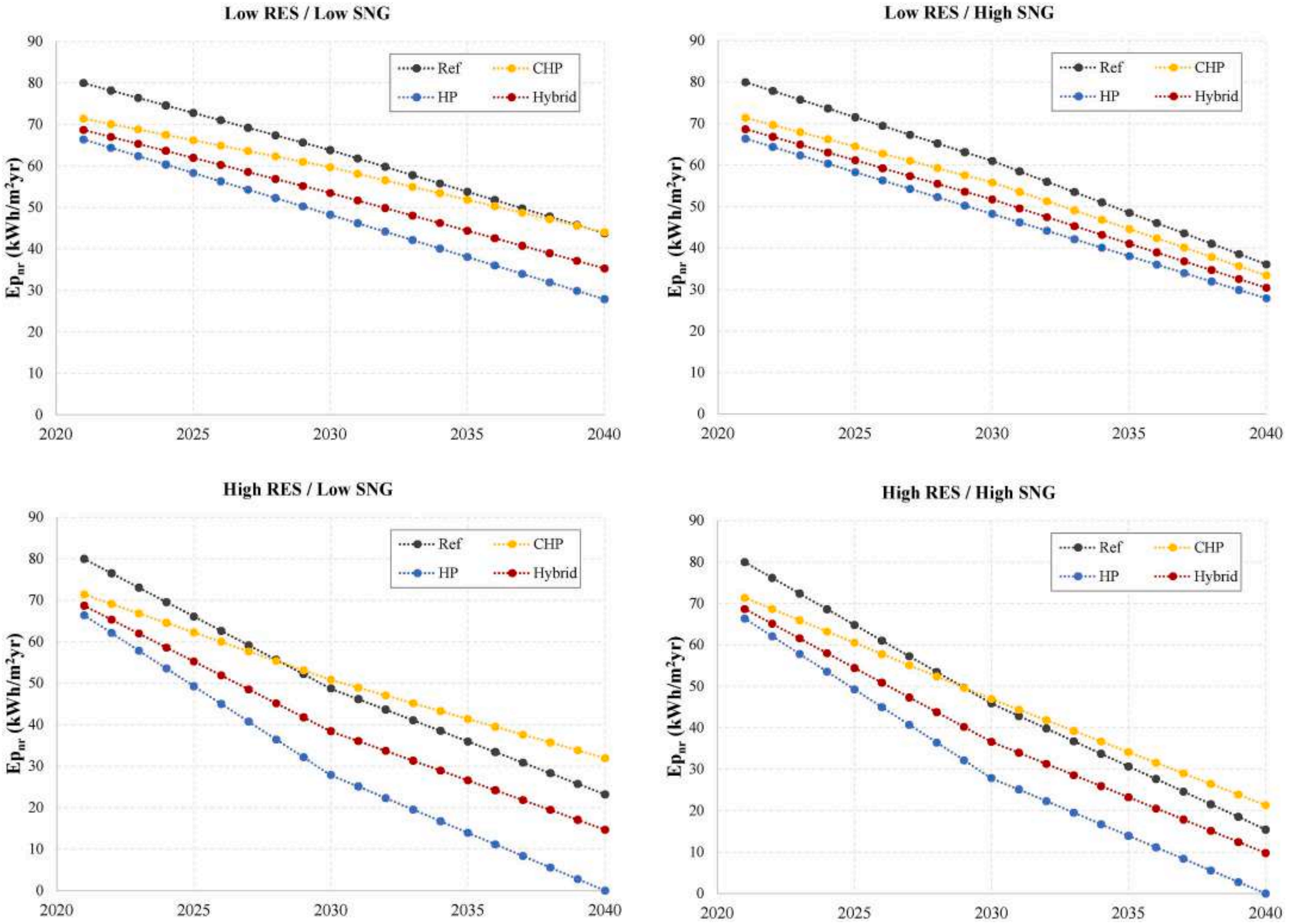

Fig. 9. Evolution of EP_{nr} over the next two decades in different decarbonisation scenarios for Low Temperature configurations.

configuration.

CO_2 emissions show the same trends as non-renewable primary energy consumption. Threshold values vary slightly, but by a negligible amount.

3.1. *Effects of decarbonisation scenarios on building system configurations*

Combining the two decarbonisation pathways for the electricity grid with those referred to the gas grid, four decarbonisation scenarios of the national energy system have been developed. In Figs. 9 and 10, the evolution of EP_{nr} over the next two decades in different decarbonisation scenarios has been depicted in LT and HT configurations, respectively.

The decarbonisation scenario significantly affects the building energy performance. Indeed, values change over time according to the increasing renewable penetration in the energy system, and the energy savings provided by the different configurations must be considered over the whole period.

The evaluation of the building system scenarios in the current situation presents different values for high and low temperature configurations. In the LT scenario, the HP application is better than the other strategies. In the HT scenario, the energy and emission savings provided by CHPs and HPs are almost equal. In both cases, any decarbonisation scenario presents HPs as the technology capable of providing the greatest energy savings over the considered time horizon.

Even in the best-case scenario for gas-fired technology, i.e., Low RES/High SNG, HPs turn out to provide higher performance. Moreover, only in that scenario, CHP systems are competitive over the entire period. Indeed, in the high-RES scenarios, CHP systems lead to less energy savings than the reference configuration already before 2030.

Typically, in the same plant configuration, primary energy consumption varies considerably over time. Building performance assessments are normally performed by analysing the exogenous parameters under the characteristic conditions at the time the analysis is performed. However, as shown in Figs. 9 and 10, EP_{nr} significantly varies over time and is influenced by national policies for energy system decarbonisation.

The specific non-renewable primary energy consumption analysed following traditional analysis with fixed factors at the reference year 2021 ($EP_{nr,2021}$) has been compared with the $\overline{EP_{nr}}$ in different decarbonisation scenarios. The same analysis has been carried out for CO_2 emissions.

$EP_{nr,2021}$ and $\overline{EP_{nr}}$ in different decarbonisation scenarios for both LT and HT configurations have been depicted in Figs. 11 and 12, respectively.

Furthermore, $CO_{2,2021}$ and $\overline{CO_2}$ in different decarbonisation scenarios for both LT and HT configurations have been depicted in Fig. 13.

The average values over the period are different from what can be observed in the present state. Depending on the decarbonisation scenario and the building system configuration, the $\overline{EP_{nr}}$ is between 17% and 55% lower than the EP_{nr} assessed with traditional analyses.

In detail, HP-based configurations are those that most improve performance over the period due to the rapid RES deployment on the electricity grid. Under current conditions, the difference in energy sav-

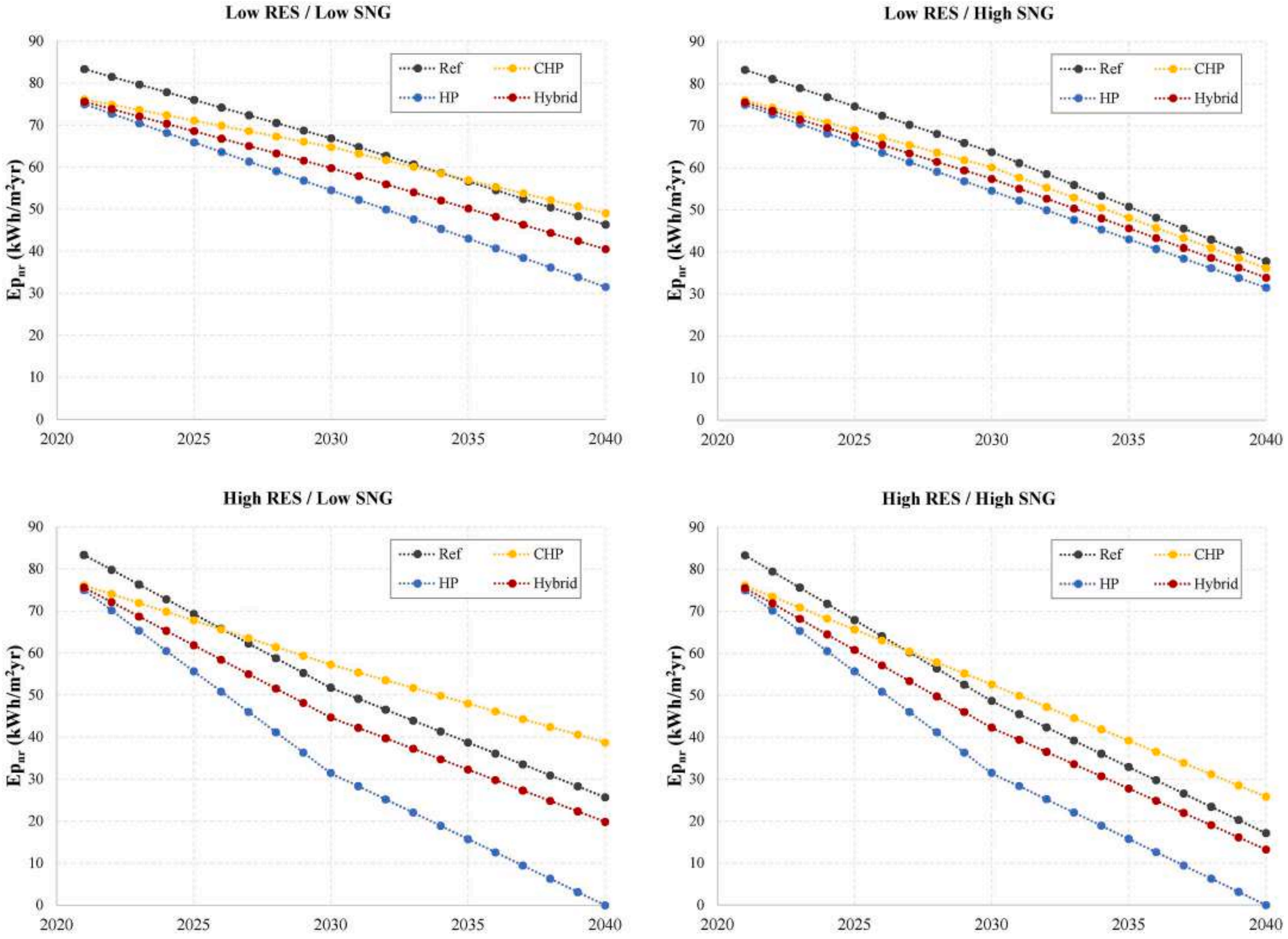

Fig. 10. Evolution of EP_{nr} over the next two decades in different decarbonisation scenarios for High Temperature configurations.

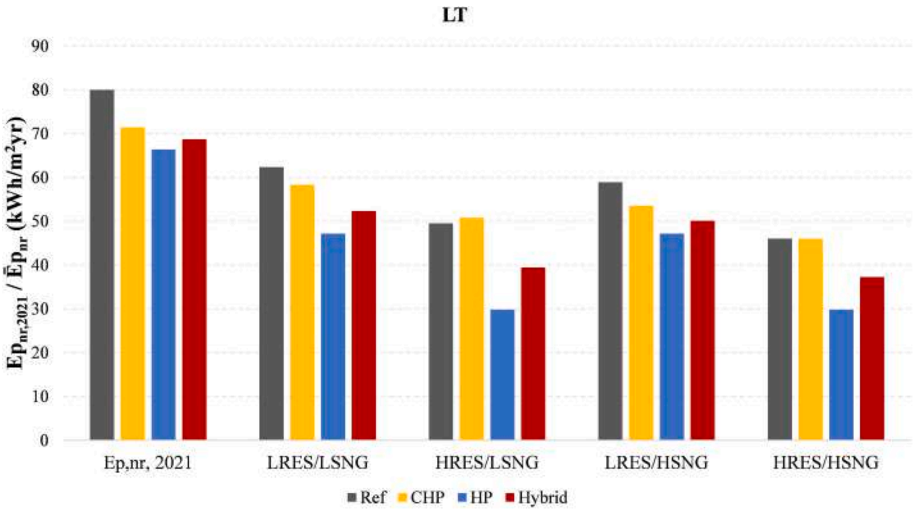

Fig. 11. $EP_{nr,2021}$ and $\overline{EP_{nr}}$ in different decarbonisation scenarios for LT building configurations.

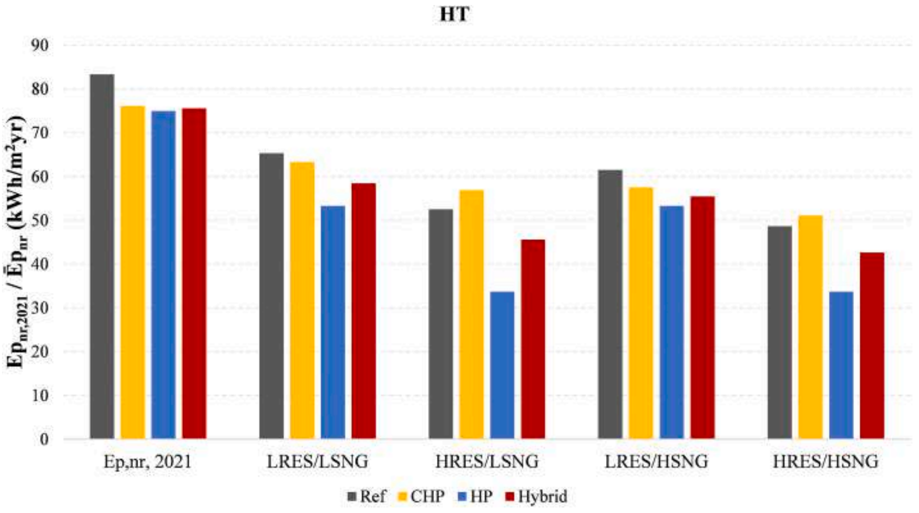

Fig. 12. $EP_{nr,2021}$ and $\overline{EP_{nr}}$ in different decarbonisation scenarios for HT building configurations.

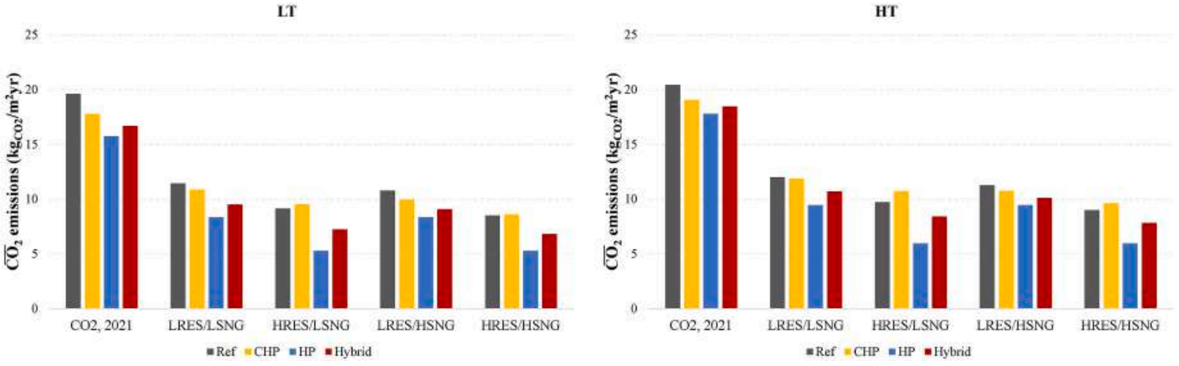

Fig. 13. $CO_{2,2021}$ and $\overline{CO_2}$ in different decarbonisation scenarios for both LT and HT configurations.

ings between CHP and HP in HT configurations is negligible. Conversely, the $\overline{EP_{nr}}$ of HP is much lower in all decarbonisation scenarios. The evaluation of savings provided by CHP plants can also be misleading. Indeed, in evaluations for 2021, such systems provide significant energy savings. However, the $\overline{EP_{nr}}$ over the period is even higher than the reference configuration in some scenarios and is highly dependent on the assumed roadmap.

Integrating forecasts on the national electricity and gas grid transformation is of utmost importance for estimating the real energy performance of buildings over the system lifetime. Most scientific studies and national building certifications, on the contrary, take grid parameters as fixed. While such an assumption allows a correct building analysis in the reference year, the national energy system transformation leads to incorrect assessments over the useful life of the building systems.

Analysing the building energy performance in its current state, without contextualising it and predicting the evolution of exogenous parameters, it may even lead to an incorrect choice of building system configuration.

Furthermore, the aspect addressed in the present article also influences the accuracy of studies analysing emissions by means of the life cycle assessment methodology. Indeed, emission factors for energy consumed from the grid are often considered as fixed. Nevertheless, as demonstrated in this work, the CO_2 emissions due to energy consumption from the grid in a transforming energy system cannot be addressed only focusing on the current state.

3.2. *Sensitivity analysis*

A sensitivity analysis by changing the COP and total efficiency of CHP systems has been carried out. The COP has been varied in the range 2.5–3.5 and 1.5–2.5 for LT and HT configurations, respectively. Furthermore, the First Law efficiency of CHP plants has been varied between 85% and 95% for conventional systems and between 99% and 107% for systems with condensing heat exchanger.

In Figs. 14 and 15, the sensitivity analysis in High RES/High SNG scenario in both LT and HT configurations have been reported for $\overline{EP_{nr}}$ and $\overline{CO_2}$, respectively.

In the considered COP ranges, HP application is still the best choice for reducing the building's non-renewable primary energy consumption and CO_2 emissions. Furthermore, even a significant increase in CHP system efficiency in the HT scenario does not allow the technology to outperform the reference scenario in the long run. On the contrary, the assumed efficiency ranges allow those systems to be competitive with the separate generation in the LT scenario.

In general, the technology efficiencies are not as decisive for the choice of the best configuration as are the exogenous network parameters. It can even be argued that the great reduction in building primary energy consumption by means of HPs is not only due to their high efficiency, but above all, to the electrification of thermal demand combined with the electricity grid decarbonisation.

3.3. *Limitations of the work and further developments*

The proposed methodology is based on some assumptions on different parameters. These values represent a simplification that allows primary energy factors to be easily correlated with the renewable energy share in the grid.

It must be highlighted that the quantitative analyses made in this article are dependent on the location of the case study. Indeed, some factors related to the national energy mix and plant characteristics influence some parameters.

Furthermore, the national average efficiencies of thermoelectric plants have been assumed to be fixed, whereas they could be improved in the coming decades. However, this assumption does not affect the findings of the work, as only a slight further improvement of HP scenario parameters could be achieved, resulting already in the present analysis as the best strategy.

Semi-dynamic modelling poses limitations in the result accuracy, as plant efficiencies have been considered according to seasonal average values. However, the discussion of these parameters has been addressed through a sensitivity analysis.

The case study has been modelled in order to consider an efficient building and the number of energy system configurations analysed has been limited to four. However, the application of the methodology to different case studies and extended to different system configurations may be the subject of future works. Likewise, the methodology presented in this paper can be easily integrated into dynamic analyses that aim to investigate the performance of heating systems.

This methodology can therefore be a tool that can be integrated into different fields of building energy analysis. For instance, the proposed approach may strongly influence the results of multi-objective optimisation studies and this aspect may be the subject of future studies.

4. Conclusion

The present work aims to assess how the renewable share increase in the electricity and gas grids can affect building refurbishment strategies. To do this, an approach to calculate energy and environmental performance of building system, taking into account the national energy system transformation, has been proposed.

In detail, a method of evaluating building performance as an annual average over the system lifetime has been proposed, as opposed to traditional analyses that consider network parameters as fixed at the reference year.

Two roadmaps for the renewable share increase in the electricity and gas grids have been assumed. Thereby, four national decarbonisation scenarios have been considered. Two typical buildings supplied at high and low temperature have been taken as a case study. Four system configurations, concerning conventional boiler, heat pump, combined heat and power plant and a hybrid system, have been analysed.

The main results can be summarised as follows.

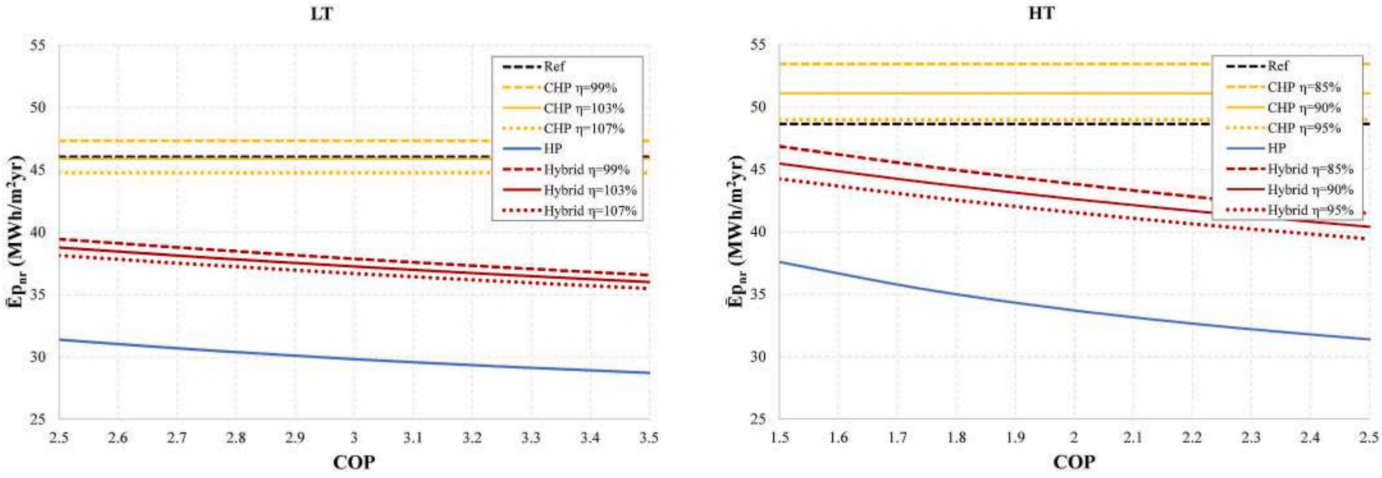

Fig. 14. Sensitivity analysis of $\overline{EP_{nr}}$ in High RES/High SNG scenario by varying COP for both LT and HT configurations.

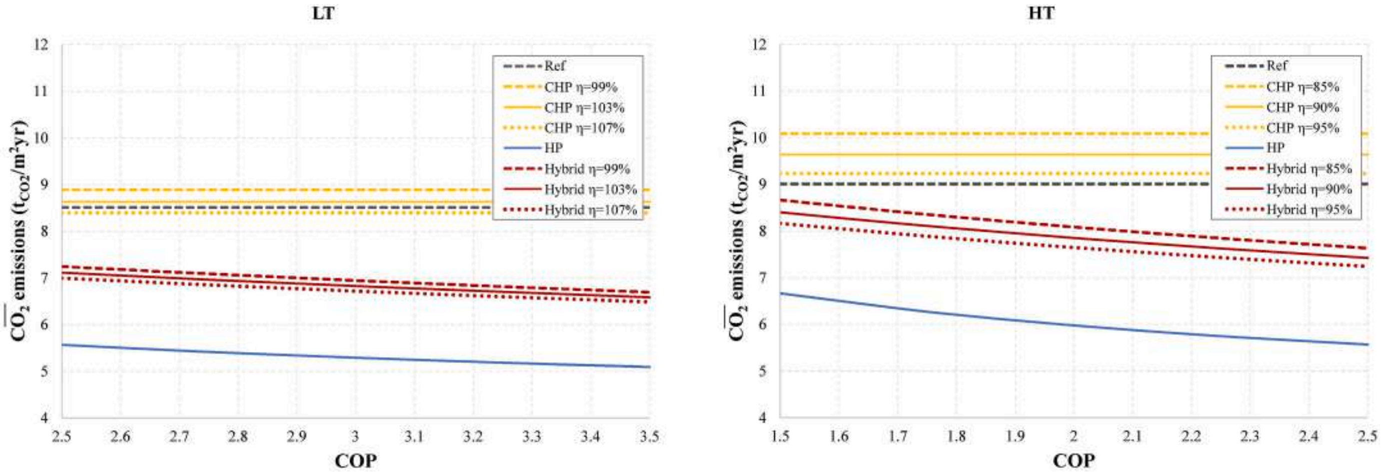

Fig. 15. Sensitivity analysis of $\overline{CO_2}$ in High RES/High SNG scenario by varying COP for both LT and HT configurations.

- Non-renewable primary energy consumption and CO_2 emissions of energy system configurations are highly dependent on the renewable share in both electricity and gas grids.
- The decarbonisation scenario significantly affects the energy performance of the building. Indeed, the latter is dependent on the primary energy associated with the energy carrier consumed in the building. Since primary energy is affected by the RES share of the grid, it is necessary to consider the parameter variation over the system lifetime. Indeed, values change over time according to the increasing renewable penetration in the energy system, and the energy savings provided by the different configurations must be considered over the whole period.
- Depending on the decarbonisation scenario and the building system configuration, the $\overline{EP_{nr}}$ is between 17% and 55% lower than the EP_{nr} assessed with traditional analyses.
- There is a threshold value of $\%RES_{el}$ for which the heat demand electrification by means of heat pumps turns out to be better than the cogeneration system application. Such a value is extremely dependent on the %SNG on the gas network. Without SNGs in the gas grid, the RES share required to make HPs the best option is lower than 40%.
- If there were no renewable energy on the power grid, combined heat and power plants would provide significant energy savings compared to other configurations. However, the competitiveness of those systems worsens sharply as the $\%RES_{el}$ increases. Furthermore, there is a threshold value of $\%RES_{el}$ for which combined heat and power systems are correlated with higher energy consumption and emissions even compared to the reference scenario.
- Any decarbonisation scenario presents heat pumps as the technology able to provide the greatest energy savings over the time horizon. In scenarios characterised by high electricity RES share, combined heat and power systems provide less energy savings than the reference configuration already before 2030.

In the next decades, energy systems will deeply change. Analysing the building energy performance in its current state without contextualising it and predicting the evolution of exogenous parameters, may even lead to an incorrect choice of plant configuration.

Taking this dynamic into account in scientific studies, as well as in the national certification of buildings, is important in order not to make erroneous assessments on the choice of the best building system configuration.

There is also a risk associated with different national certifications of building performance. If, as is the case in Italy for instance, primary energy factors are updated by the competent bodies, the same building certified in different years gets different energy performance indicators. This issue may lead to unevenness in certification values.

The aspect addressed in the present article also influences the accuracy of studies analysing system emissions by means of the life cycle assessment methodology. Indeed, emission factors for energy consumed from the grid are often considered as fixed. Nevertheless, as demonstrated in this work, the CO_2 emissions due to energy consumption from the grid in a transforming energy system cannot be addressed only focusing on the current state.

Finally, the present work can give insight for policymakers in order to modify national regulations, which, by not taking into account the energy system evolution, risk penalising heat pump systems and delaying the transition towards full electrification of building stock.

Credit author statement

Lorenzo Mario Pastore: Conceptualization; Methodology; Formal analysis; Writing – original draft, Writing – review & editing, Gianluigi Lo Basso: Writing – review & editing, Livio de Santoli: Supervision.

Declaration of competing interest

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

Data availability

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

Nomenclature

COP Coefficient of Performance (–)

CO_2specific CO_2 emissions (t_{CO2}/m^2yr)E_{el}Annual electricity consumption (MWh/yr)E_{gas}Annual gas consumption (MWh/yr)EP_{nr}specific non-renewable primary energy consumption (kWh/m^2yr)η specific CO_2 emissions (t_{CO2}/m^2yr)E_{el}Annual electricity consumption (MWh/yr)E_{gas} Annual gas consumption (MWh/yr)EP_{nr}specific non-renewable primary energy consumption (kWh/m^2yr)ηefficiency (–)

η_{thel}Average efficiency of national thermoelectric plantsf_cCorrection factor (−)$f_{e,el\ grid}$emission factor (−)f_{nr}non-renewable primary energy factor (−)
P   Average efficiency of national thermoelectric plantsf_cCorrection factor (−)$f_{e,el\ grid}$emission factor (−)f_{nr}non-renewable primary energy factor (−)PPower (kW)
PFEC   Primary Fossil Energy Consumption (MWh/yr)

%RES$_{el}$RES share in electricity grid (−)%SNGSNG share in gas grid (−)Subscripts

Boil	Boiler
D	Demand
el	electricity
GRID	taken from power grid
nr	Non-renewable
TES, in	Injected into thermal Energy Storage
TES, in	Taken from thermal energy storage
th	thermal
t	time

Abbreviations

CHP	Combined Heat and Power
HP	Heat Pump
HT	High temperature
LT	Low temperature
NG	Natural Gas
RES	Renewable energy sources
SNG	Substitute Natural Gases
TES	Thermal energy

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