Hybrid Heat Pump Systems as a Possible Solution for the Energy Transition Towards Sustainable Heating Systems for Buildings

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Hybrid heat pump systems as a possible solution for the energy transition towards sustainable heating systems for buildings

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Abstract. Heating of residential buildings is one of the main sectors contributing to the overall primary energy (PE) consumption worldwide. Therefore, many efforts have been done to make new buildings more energy efficient, such as increasing the insulation level and adopting more sustainable heating systems. In this field, heat pumps (HP) are seen as the most promising heating technology. However, they have some drawbacks that limit their spread at large scale, especially in existing buildings, for domestic hot water (DHW) production and in cold climates. The adoption of hybrid systems (HS) can mitigate this phenomenon through the application of a second generator, a condensing boiler, that helps the heat pump during its periods of inefficient operation. The purpose of the present research is the identification of the area of application and the best control strategies for HS, to allow them to be a valid substitute for fossil-based heating systems in existing and thus less insulated buildings.
Different hybrid system configurations, as well as climates and types of building have been simulated. The results have been compared in terms of PE consumption. In addition, a cost evaluation has been conducted.
The results show that HS can lead to important benefits, especially for buildings with high energy needs. The results of the research proved that HS could contribute to increase the PE savings of older and less insulated buildings, which represent the large majority of the building stock. In this perspective, hybrid systems are a viable solution to be applied for the energy transition towards more sustainable buildings.

Keywords: Sustainable buildings, Hybrid systems, heat pumps.

1 Introduction

The Paris agreement, signed in 2015 by 196 countries, was the first crucial step towards the global energy decarbonization, with the aim of limiting CO_2 emissions and so the global temperature increase within 2°C. The rapid development of climate change imposes the urgent need to industrialized countries to reduce their energy consumptions, lower the use of fossil fuels, and consequently, to reduce the emission of greenhouse gases (GHG). In this sense, through the European Green Deal, Europe is committed to

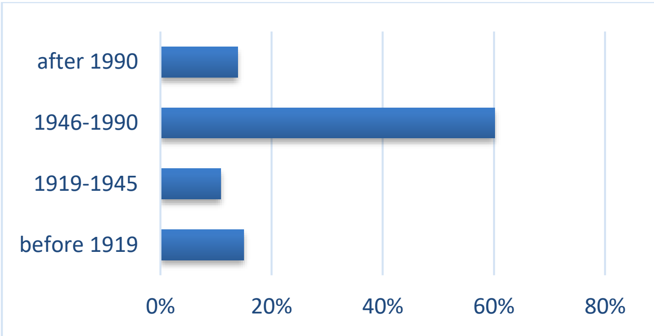

Fig. 1. Residential buildings distribution by construction year in Italy

become carbon neutral within 2050 [1]. To reach this goal, it is necessary to act on many aspects of the society, by investing in sustainable technologies, decarbonizing the energy sector, and changing towards more environmentally friendly and clean means of transport. Not least, the energy efficiency of the building sector must be addressed, also according to the EU plan. In 2018, households were responsible for 26% of the final energy consumption in the EU [2]. The greatest part was required for heating the house, that, together with hot water consumption, reaches almost 80% of residential building energy needs. In fact, new buildings can reach high energy efficiency levels (e.g. energy consumptions below 10- 50 $kWh/m^2\ y^{-1}$) due to the high-level construction standards applied. However, new buildings, built according to these standards, represent only a very small fraction of the building stock. EU statistics show that approximately 50% of buildings were constructed before 1970, so prior to the introduction of any building energy efficiency regulation [3]. In Italy, the first regulation addressing energy efficiency in buildings came into place in 1990. Most of the existing buildings, 84%, according to a report presented in 2015, were built before that time [4]. It is therefore crucial, in the perspective of the energy transition, to make existing buildings more sustainable.

In the HVAC (heating, ventilation and air conditioning) sector, the heat pump technology is becoming more and more popular and it is considered as the technology that, applied at large scale, will make a substantial contribution to the sector's decarbonization. This tendency is confirmed by the rate of sales, that reached double digit growth in Europe in 2018 [5]. Heat pumps have a high efficiency, as they can produce 3 or 4 times the amount of heat that they consumed as electric energy. This factor depends on the efficiency of the heat pump, which is expressed by the COP (coefficient of performance). For comparison: a simple electric heater converts energy into heat at a ratio of 1:1. The heat pump instead uses electricity to operate the compressor and extract heat from the ambient, through a thermodynamic vapor compression cycle, even if the outside temperature is below the indoor temperature. This process has a higher efficiency than the 1:1 conversion operated by electric heaters, and this efficiency is identified by the COP. Moreover, HP exploit a fraction of renewable energy, as they take heat from the ambient. The COP depends in the first place on the Carnot efficiency, i.e. from source and sink temperatures. Source and sink temperatures are in this case defined by the ambient and by the supply water temperature. The higher the difference between these temperatures, the lower will be the efficiency of the heat pump. For this reason, heat pumps are applied more frequently in new houses, which use low temperature heating emission systems, as radiant panels, requiring water at low temperature from the heat generator. Existing buildings are usually poorly insulated and not provided with radiant panels, even after renovations. Therefore, high supply water temperatures are required from the generator, thus increasing the difference between source and sink temperature and reducing the heat pump efficiency. For the same reason, DHW production is also inefficient with heat pumps, as it requires high supply water temperatures.

Air-to-water heat pumps (ATW HP), the type of heat pump that uses the ambient air as heat source, suffer the most. However, ATW HP are the most widespread HP systems, due to their easiness of installation. Therefore, the present article focuses on this type of HP.

To reduce the previously mentioned drawbacks of the HP a second generator can be added. Thus, the HP operation can be avoided or supported in critical periods. Moreover, a smaller HP size can be chosen, as the second generator can operate during peak loads. Electric heaters are usually provided as HP integration. Their operation decreases the overall system efficiency, as it should be remembered that they convert the electric energy with a ratio of 1 to 1 in heat. Instead, the adoption of natural gas boilers as second generator with ATW HPs has gained interest in recent years. Natural gas boilers are more efficient than electric heaters in terms of primary energy consumption and, in some circumstances, they can even be more efficient than HPs. They can improve the overall system efficiency, by substituting or integrating the HP when the ambient temperature is low or when the supply water temperature is high.

Some scientific papers and reports made forecasts about the effect of the deployment of hybrid systems at large scale ([6-9]). They concluded that hybrid heat pump systems can be seen as an important resource for the energy transition. The applications of heat pumps can be broadened, thanks to the presence of this second generator. Moreover, the partial transition towards full electrical heating systems may reduce the need for electric peak load power, allowing for more HP systems as heating system in the electric grid and providing more flexibility since the gas boiler can also bridge shorter periods. Hybrid systems could therefore be integrated in smart energy systems. The result will be a reduced cost for users and society for the energy transition towards more sustainable building heating systems, and presumably a more rapid process.

The management of this kind of systems plays a crucial role for its efficiency. The choice of the configuration and of the control strategy can modify PE consumptions in a significant way. This aspect has not yet been studied in a comprehensive way in research. Some authors addressed their study to the combination of ATW HPs and gas boilers, comparing the efficiency of hybrid systems with that of monovalent — heat pump-only or boiler-only — solutions ([10-14]). Nevertheless, most of these studies performed the analysis for a determined city and climate, some of them did not perform simulations of the whole heating season, or the building characteristics were not changed. Most of the studies did not consider the combination of DHW production and

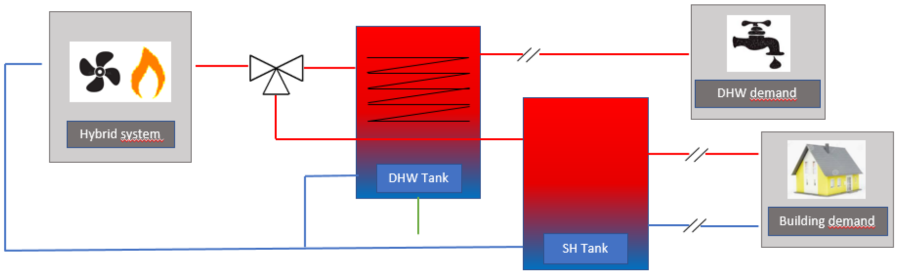

Fig. 2. Simplified layout of the dynamic building simulation logic

space heating (SH), but considered only the latter. This study focuses on hybrid systems (HS) composed by an ATW HP and a natural gas boiler. The purpose of this work is to compare a HS with a heat pump-only system in terms of primary energy (PE) consumption, varying the building characteristics and the climate to which the system is applied, in order to assess which system makes the greater contribution to the energy transition under which circumstances. In this way the reader can gain an overview about the application of HS. After that, an economic evaluation is presented, with the aim of understanding if HS can be a feasible solution to be applied in the energy transition, not only from an efficiency point of view, but also economically.

2 Material and Methods

The primary energy consumption of a hybrid heating system or an only-heat pump system, combined with a heating plant and a building, have been simulated using a building dynamic simulation software, replicating a whole calendar year.
The layout in fig. 2 shows the hydraulic configuration of the simulated heating plant. When the temperature in the hot water tanks for DHW and SH decreases below the set point value, the heat generator — i.e. the hybrid system in the figure, but also the heat pump-only — produces hot water that serves either the SH tank or the DHW tank, giving the priority to DHW production. Hot water from the DHW tank is taken directly from the users' domestic needs. The SH tank is connected to the heating emission system, i.e. radiant panels (e.g. floor heating) or radiators, that transfer heat to the rooms.
The set point of the DHW is assumed to be 55°C, while the set point of the SH tank is variable according to the heating emission system used and as a function of the ambient temperature. If radiators are applied, the design SH set point temperature is 52°C, while for radiant panels, the design set point temperature is set to 40°C. The set point temperature then decreases when the ambient temperature increases, following the trend of the heating demand.
The model of the hybrid system — i.e. the model of the heat generators and their control logic — has been implemented through a technical computing language, and afterwards combined with the building simulation. Performance data from manufacturers, including the data at part load operation, have been used for the simulation of the behavior of

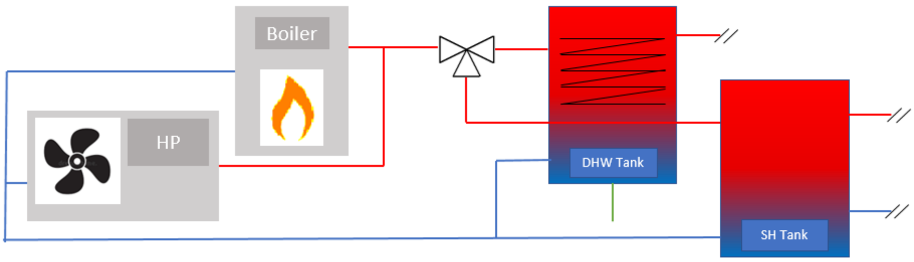

Fig. 3. Alternate Parallel (AP) configuration layout

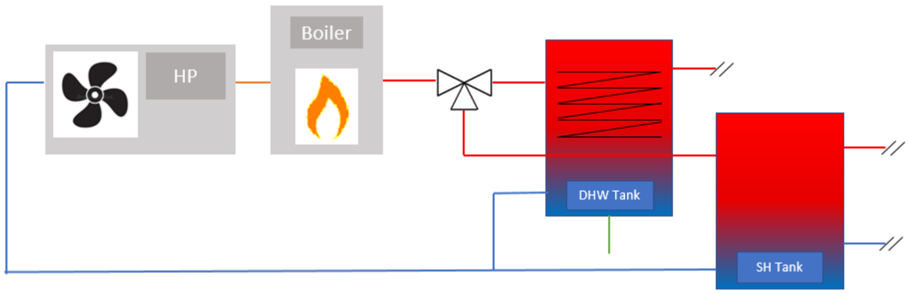

Fig. 4. Series (S) configuration layout

the boiler and the heat pump, with the aim of accurately reproducing the generators' real-world performances. Data of modulating inverter heat pumps and a condensing boiler have been considered. The heat pump efficiency is mainly influenced by two phenomena, namely the on-off cycling and the defrosting cycles. The associated performance reductions have been considered according to the experimental results of previous research on these subjects ([15-17]).

The control logic is the core of the hybrid system. It decides which of the two generators is in use. In this paper, two different control logics, and corresponding system configurations, have been implemented and compared. The first, and the simpler, is the alternate-parallel (AP) configuration. In SH mode, for ambient temperatures above a predetermined threshold temperature (TT), only the heat pump operates. When the ambient temperature is below TT, only the boiler operates. The whole DHW demand is provided by the boiler. The layout of the configuration is shown in fig. 3. The second control logic is the configuration in series (S). In this case, the return water firstly passes through the heat pump and afterwards trough the boiler. Thus, the boiler receives the heated HP leaving temperature (fig. 4). In this way, the HP can produce water at a lower supply temperature since the difference to the set point temperature is covered by the boiler. This increases its efficiency. Three operation ways are possible: heat pump only operation, boiler only operation or combined operation. The combined operation takes place when the HP is not able to provide the requested heat load, or when its operation is not efficient enough and its leaving water temperature is lowered below the set point temperature.

The comparisons between the HS configurations were performed for different climates, building characteristics and DHW demand.
The analysis of the influence of the climate in which the system operates is based on the climatic data of two European cities, namely Strasbourg and Prague. According to the analysis performed by Pernigotto and Gasparella [18], the climates of these two cities are representative for two types of climates widely present in Europe: a cold and a moderate climate. Taking the climates of the two forementioned cities generalizes the results for a large part of the EU.
Two insulation levels were taken as reference for modelling a single-family residential house, simulating Italian buildings of the 80ies and of the 90ies with the corresponding thermal insulation, respectively named H1 and H2.
The effect of the quantity of domestic hot water used on the PE consumption was assessed for building H2. Two demand sizes are used, corresponding to a DHW volume per day of 225 and 500 liters respectively.
Varying the forementioned parameters resulted in six cases, which are identified and summarized here below:

- Case 1: refers to the building H1 (less insulated), in the cold climate, with 225l DHW demand per day
- Case 2: refers to the building H1 (less insulated), in the moderate climate, with 225l DHW demand per day
- Case 3: refers to the building H2 (more insulated), in the cold climate, and with 225l DHW demand per day
- Case 4: refers to the building H2 (more insulated), in the moderate climate, and with 225l DHW demand per day
- Case 5: refers to the building H2 (more insulated), in the cold climate, and with 500l DHW demand per day
- Case 6: refers to the building H2 (more insulated), in the moderate climate, and with 500l DHW demand per day

3 Results

3.1 Results presentation

Table 1 summarizes the results from the analysis as relative PE savings of the hybrid system compared to the only heat-pump system. Case 1, corresponding to the less insulated building with radiators (H1) in the cold climate, shows PE savings of 21.3% and 21.7%, respectively for the alternate parallel (AP) and series (S) configuration. Case 2 shows the results for the same building H1, located in the moderate climate. The savings achieved through AP and S configuration are approximately 16% and 17%. Case 3 and 4 refer to the simulations performed with the newer building in which radiant panels are applied (H2). PE savings achieve values of 8.8% and 11.4% for the building located in the cold climate, and 5% to 8% in the moderate climate. The objective of the analysis performed in case 5 and 6 was to understand how the variation of the DHW demand size affects the results. Building H2 is used as reference and the resulting PE savings go from 10.4% to 13.6% for the cold climate, and from 5.1% to 9.8% for the moderate one.

Table 1. PE savings [%] of hybrid systems configurations AP and S, compared with the only HP configuration

		Cold climate				Moderate climate		
		HP	**AP**	**S**		**HP**	**AP**	**S**
less insulation	**CASE 1**	0.0%	21.3%	21.7%	**CASE 2**	0.0%	16.1%	17.1%
more insulation	**CASE 3**	0.0%	8.8%	11.4%	**CASE 4**	0.0%	5.0%	8.8%
more insulation higher DHW	**CASE 5**	0.0%	10.4%	13.6%	**CASE 6**	0.0%	5.1%	9.8%

3.2 Discussion

The results presented in the previous paragraph highlight the fact that the building characteristics and the climate have a remarkable influence on HS performance. The savings are higher when the building is less insulated and located in a cold climate. Looking in more detail on case 1 to case 4, which satisfy an equal DHW demand, it can be noticed that savings are lower when the building energy demand is lower. From case 1 to case 4 the energy demand decreases from 191 $kWh/m^2/y^{-1}$ to 97 $kWh/m^2/y^{-1}$ and correspondingly the maximum saving obtained with the HS decreases from 21.7% to 8.8% (see fig. 5). The building energy demand is higher, when the ambient temperature is colder and when the building is less insulated, which normally also requires the use of heating systems with higher supply water temperatures. Both conditions worsen the HP performance but not the performance of the gas boiler. The condensation phenomenon occurring in the boiler, which improves its efficiency, is not affected by the different case conditions as the return temperatures levels are always suitable for condensation to occur.

As well as the building energy demand, also a higher DHW demand seems to influence the HS performances in comparison with an only-HP system, causing again an increase in PE savings. As previously discussed, the high supply water temperatures required for the DHW production reduce HP performances and lead to an advantage in terms of efficiency for the HS application.

The most convenient hybrid configuration is the S one, in all four cases. However, the difference with AP in case 1 and 2, respectively 0.4% and 1%, is not significant. This makes AP the best solution for case 1 and 2, as the S configuration requires a more complex installation and control logic, without bringing relevant benefits. Cases 3 to 6 benefit instead from the application of S configuration, as the high PE savings compensate for the more complex design. The fact that old and poorly insulated building are the main cause of the building sector energy consumption was previously discussed.

The results of the present analysis prove that HS can significantly reduce the need for PE due to space heating especially of those buildings. This is a key aspect to be considered in an energy transition perspective.

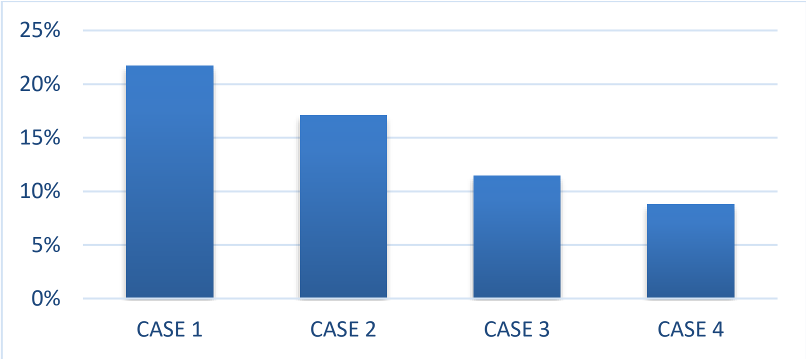

Fig. 5. PE savings [%] for series configuration with respect to the only-HP configuration for case 1 to 4

The improvement of old buildings is often complex, requiring deep and expensive renovations, that most of the time are hardly applicable — e.g. when the fragmented ownership structure in apartment buildings prevents a uniform solution, or because the installation of floor heating systems requires a complete reconstruction.
The novelty of the approach lies in the fact that, through the application of HS, a relevant amount of PE can be saved, even without the need for major refurbishments. The largest part of existing buildings already uses a boiler for heating purposes. With the adoption of a HS, a heat pump must be added to the heating system.
The most important benefit is that HS allow for substituting of boiler only solutions in less insulated buildings where HP are not efficient. This means that part of the heating capacity is provided by renewable energies, where previously only fossil fuels were used for heating. A further positive aspect is that HS can accelerate the spreading of the heat pump technology, in such a way that it will be gradually known and accepted by the users, usually suspicious and less confident towards new heating technologies. The combination with a traditional one can improve its acceptance.
A cost evaluation of the proposed HS configurations is however necessary to quantify the benefits for the users in economic terms, which lead to decisions for or against its adoption.

4 Cost Analysis

The cost analysis is based on the net present value (NPV) method. In this way it is possible to compare and sum the expenses for the purchase of the heating system with the ones during operation.
Initial investment costs, as well as the cost for electricity and natural gas that will be due within the lifetime of the heating system — 20 years — have been considered in the evaluation. Possible subsidies were not included in the analysis. Initial prices for the generators, heat pump and boiler, are reference market prices provided by manufacturers. An additional price has been added to all hybrid configurations to consider the additional control logic needed for the management of the combined operation of

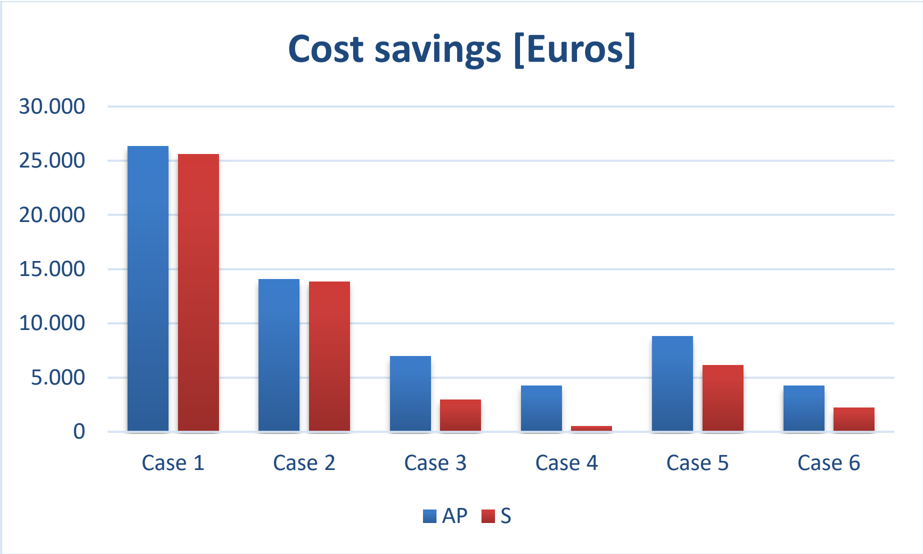

Fig. 6. Cost savings for 20-year lifetime compared to the HP-only solution for case 1 to case 6, for the hybrid configurations AP and S

the two generators. The determination of the actual prices of natural gas and electricity refers to the data available on the web-portal belonging to ARERA [19] — Italian authority for the regulation of electrical networks and environment — and so, they reflect the price situation in Italy in April 2021.

The results of the cost analysis are reported in fig. 6. The cost savings (in Euros) of the hybrid solutions, alternate parallel (AP) and series (S), compared to the reference case, i.e. the heat pump-only solution, are shown for the 6 cases identified in the previous paragraphs.

The most convenient solution for each case is the AP configuration, as it reaches higher cost savings, compared to the heat pump-only solution, than the S configuration, within the lifetime of 20 years. The AP solution uses the boiler more often than the S solution, and because of the low cost of natural gas as a primary energy source it results as the most convenient solution. Considering case 1 and 2, the difference in cost savings between AP and S is minor, but the savings of both the configurations compared to the heat pump-only solution are significant, reaching more than 25,000 Euros during 20 years of operation.

The results of the cost analysis for case 1 and 2 lead to similar conclusions as those obtained in the primary energy analysis, i.e. both the hybrid configurations achieve important cost and PE savings compared to the heat pump-only solution. Higher cost savings are achieved in the cold climate, compared to the moderate climate, therefore in case 1, 3 and 5 compared to case 2, 4 and 6, as it was observed also in the PE analysis. However, in the PE analysis the S configuration resulted to be the most efficient, while in the cost analysis the AP configuration is the most convenient. If the optimization of the PE is chosen, and the S configuration is used, the cost savings that the hybrid system

can achieve in the moderate climate with the more insulated building (case 4) are very small (approximately 500 Euros). Higher cost benefits are achieved in case 5 and 6, in which a higher DHW demand is applied, compared to case 3 and 4.
In the perspective of the transition towards more sustainable heating systems the present cost analysis shows how hybrid systems can mitigate another drawback that heat pump systems still have, namely the low incentive for customers to purchase them from an economic point of view. As the analysis shows, the heat pump-only solution is not economically convenient, especially for high heating demands. Hybrid systems could be therefore suitable for the energy transition wherever users do not consider a heat pump due to the poor price-performance ratio and continue to rely on fossil fuels even when renewing the heating system. Both PE and cost analysis show that the only-heat pump solution becomes more convenient the higher the insulation level of the building is and when low temperature heating emission system are used, such as radiant panels. For this reason, hybrid system would be a viable transitory solution for those building that still do not have a high thermal insulation level and are not provided with radiant panels, as these types of renovations are often quite expensive and hard to implement.
Also from a macroeconomic point of view, the public infrastructure could benefit from the application of hybrid systems, as the peaks in heating demand are split between heat pump and boiler, thus reducing the need for electrical grid expansion for short but high peak loads on cold winter days. The advantage continues also at user level, as the reference power of the electricity meter can be reduced, which has a great impact on the electricity bill. For all this reasons, hybrid systems can accelerate the spreading of the heat pump technology, not only in new houses, but also in existing less insulated buildings as part of a HS solution.

5 Conclusions

The present paper focuses on hybrid systems composed by air-to-water heat pumps and natural gas boilers. The purpose of the study is to define situations in which HS can be efficiently applied, varying parameters such as building insulation level and climate. Furthermore, a cost evaluation analyzes the convenience of HS solutions from an economic point of view.
To reach these goals, a model of the HS was developed and applied in a building simulation. The results have been compared in terms of primary energy consumption. In addition, a cost analysis has been conducted: initial investment costs and operating costs have been considered. The results show that important benefits can be achieved through the application of HS, both in terms of cost and PE savings, compared to a heat pump-only solution. This is true especially for applications with high DHW demands and buildings with high heating demand.
The results depend on the hybrid configuration that is implemented. In this study, two different configurations, a parallel arrangement of HP and boiler in which the two systems are used alternately (AP) and a more complex arrangement in series (S), have been implemented and compared. Configuration S shows to be more convenient in terms of

PE savings whereas configuration AP must be preferred from an economic point of view.

The novelty of the study is the identification of circumstances in which a hybrid system composed by a air-to-water heat pump and a natural gas boiler is a viable solution to replace heating systems that use fossil fuels, and where heat pump alone would be too inefficient or heating with it too expensive. The study shows that this is true especially for older buildings with a high energy demand. Renovations are often expensive and difficult to realize, so that substituting existing heating systems based on fossil fuels with HS is a possible way to generate part of the heating power with renewable energies. Putting the focus on heating of this older and less insulated buildings is important in an energy transition perspective, as they represent the majority of the building stock, and will continue to do so for several decades.

The scope of the study was to provide the basis for the correct application of hybrid systems. The proven advantages in certain conditions, especially in cold climates and for older buildings, shall help to spread the technology of HS and as consequence also to broaden the application of heat pumps, altogether accelerating the sustainable energy transition.

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