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Simulation of Efficiency of Different Configurations of Residential Hybrid Heating Systems Combining Boiler and Heat Pump

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ABSTRACT

The contribution of residential buildings primary energy consumption in the U.S. accounts for more than 20% of the total. In this context, improving the efficiency of heating systems represents a key point for keeping up with the carbon reduction goals. Air-to-water heat pumps are a promising technology that has been deeply studied in recent years. Their main advantage is to improve the share of renewables. Nevertheless, they have some drawbacks, such as the poor efficiency at low ambient temperatures and at high supply water temperatures, necessary e.g. for domestic hot water production and in high temperature heating systems. The latter can be found in a high percentage of the building stock.

Hybrid systems combining heat pumps and boilers (HHPS) can represent a viable solution to overcome these issues. The sizing of the generators and the control logic according to which they are operated play an important role in the performance of the system. For this purpose, comprehensive studies analyzing different types of buildings in different climates and considering both space heating (SH) and domestic hot water (DHW) production are still missing in the literature.

The aim of this work is to identify the best configuration of system, in terms of primary energy consumption, for different heating loads. To do so, a model of the hybrid system is firstly developed by means of a technical computing language (TCL) software. It includes the control logic, that manages the switching of the devices according to the operating conditions. The TCL model has been combined with a dynamic building simulation (DBS). Two different configurations of HHPS were analyzed varying different parameters, such as building thermal insulation, type of heating emission system, DHW demand profile and climate, with a corresponding demand of SH and DHW. The hybrid configurations are compared to a heat pump only solution.

The paper presents the results of the simulations with the aim of identifying the most efficient system configuration for each set of parameters considered, in terms of primary energy consumption.

Keywords: Hybrid system, heat pump, boiler, simulation

1. INTRODUCTION

Both in the US as in the European countries, the consumption of the building sector represents one of the main contributions of the total energy consumption (European Environment Agency, 2018), (European Commission, 2018), (U.S. Energy Information Administration (EIA), 2019). The heat pump technology has seen a rapid growth in the last years due to its favorable characteristics. It represents nowadays the most promising technology for reducing the carbon footprint of heating systems. The system is also appreciated due to its versatility: a heat pump can be applied to produce heating, cooling and DHW in one single appliance.

The efficiency of heat pumps has seen a remarkable growth over the last decades, thanks to the improvements in components and system integration. Air-to-water heat pumps represent nowadays the most widespread type of heat pump installed. However, the efficiency is strongly affected by ambient temperature and supply water temperature. The lower the ambient temperature, the less efficient the heat pump is. The same happens when a high supply water temperature is required. The heat pump should be sized for covering the peak load, thus it will be oversized for the rest of the heating season. Even if inverter driven heat pumps are used, oversized heat pumps still suffer from COP degradation for a large part of the year (Bee *et al.*, 2016).

Moreover, in the Italian building stock, most of the houses were built before energy conservation laws went into effect. Therefore, most of these buildings have poor insulation levels and require high supply water temperature for heating (ISTAT, 2015).

To overcome these problems, one possible solution is the combination of the heat pump with a second heat generator.

Heat pumps are often provided with an auxiliary generator. Commonly they are provided by manufacturers with an electrical heater, that can cover the peak loads and increase the supply water temperature, if required, compromising however the efficiency of the system. The combination of air-to-water heat pumps and gas boilers has also been proposed. The main advantage of providing the system with an auxiliary generator is that it can be operated in those situations where the heat pump works inefficiently. Moreover, the heat pump must not be dimensioned for the peak load of the building, improving its operation in mid-seasons.

Some authors already addressed their research to the study of air-to-water heat pumps in combination with gas boilers. According to several studies hybrid heat pump systems (HHPS) could represent a viable path for the decarbonization of heating systems due to its versatility: the hybrid solution could decrease the peak of electricity demand and lower the requirements for the distribution heating networks. The combination of different technologies can achieve important results in terms of emissions, the cost reduction for users and energy systems (Zhang *et al.*, 2018), (Imperial College, 2018), (Delta Energy & Environment Ltd, 2012).

Park *et al.*(2014) assessed a hybrid system serving the heating and DHW demand of a 100m^2 house. The production temperature is kept fixed at 60°C and the size of the heat pump is also fixed. The results of the study showed a convenience in the adoption of the hybrid system compared to the boiler. Klein *et al.* (2014) analyzed a system composed by a heat pump and a boiler connected in series and a storage tank. The system operates for the space heating of a 132m^2 apartment. Two different building types (and heating loads) were considered in the analysis. The hybrid system showed advantages in terms of cost compared to the heat pump system. Li & Du (2018) analyzed the performance of a hybrid system with fixed heat pump capacity applied to a residential house for space heating and DHW production. According to the author’s results, hybrid systems can achieve cost reductions both in space heating (6 to 70%) and DHW production (20 to 65%) compared to boilers. Di Perna *et al.* (2015) applied a model built on experimental data of a hybrid system to a single family house in Milan. They compared the efficiency of the hybrid system with the conventional solutions, such as a heat pump provided with electric heater, a condensing boiler and an oil boiler. They proved that the hybrid system reduces the primary energy need considerably, compared with the other solutions, while the heat pump with the electric backup heater resulted as the worst solution in terms of primary energy consumption. In terms of annual costs, the hybrid solution resulted as the most efficient one. In the analysis of Dongellini *et al*. (2017), the authors tested several combinations of heat pump, boiler and electric heater and applied the system to a 134m^2 single family house, located in the north of Italy. The hybrid solution with an optimal size of the heat pump leads to 2-3% primary energy savings, compared to the only heat pump case, and 32-34% savings compared to the only boiler case.

Even though the results of the previously mentioned studies are interesting for understanding the potential application of hybrid systems, a comprehensive study comparing the performance of a HHPS – providing both space heating and DHW and considering at the same time different climates, different types of building and DHW demand profile – is still missing.

The aim of the present study is to identify in which cases the HHPS can be a convenient solution in terms of primary energy demand. Hence, different building insulation level, heating emission systems, DHW demand profile and climates are considered in the analysis. Following the system sizing for each configuration, the systems were simulated, and the results were compared in terms of primary energy consumption.

2. METHODOLOGY

The assessment of the performance of a hybrid system started with the development of a model of the system. The HHPS model has been developed through TCL, and afterwards it has been combined with DBS. The co-simulation was run varying different parameters, such as building insulation level, heating emission system, DHW demand profile and climate in order to understand the influence of these variables on HHPS performance with respect to a reference heat pump system.

2.1 Hybrid System Model

In this simulation, the components of the hybrid system (heat pump and boiler) are connected in parallel, and the control logic simulates an alternate operation. Exceeded a threshold outdoor temperature, the system switches from boiler to heat pump operation. The ambient air temperature at which the switch between heat pump and boiler occurs has been determined through several simulations for each case. According to the operation scheme, one or two switching temperatures must be chosen:

- In the first operation strategy (OS1), DHW is always provided by the boiler, while space heating is covered by the heat pump if the temperature is higher than the threshold. (Figure 1)
- In the second one (OS2), the heat pump and the boiler provide both space heating and DHW, but with a different optimal switch temperature (Figure 2).

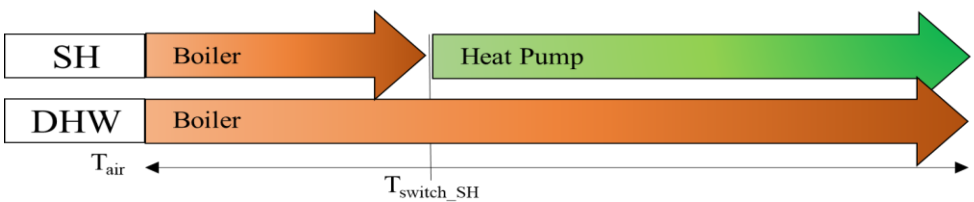

Figure 1: OS1 control logic

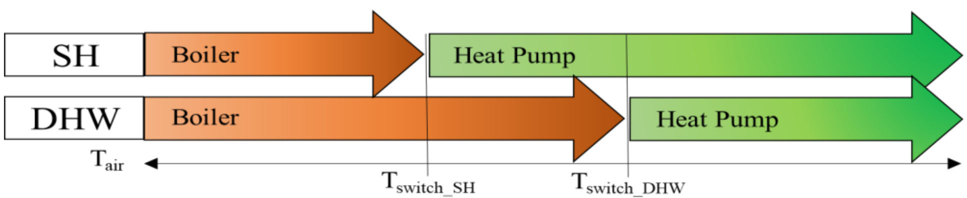

Figure 2: OS2 control logic

The heat pump and the boiler models are based on manufacturer's performance map and consider the performance degradation due to part-load operation.

The boiler is a modulating condensing boiler, with a nominal capacity of 35 kW and a minimum percentage modulation of 10%. The air source heat pump is a R-410A unit, with axial fan and inverter driven compressor, with a capacity ranging from 8 to 30 kW at 7°C air temperature and 35°C supply water temperature and a minimum percentage modulation of 40%.

Several papers in the literature addressed the problem of heat pump defrosting cycles. This is an aspect that strongly affects the performance of air-to-water heat pumps. Zhu *et al.* (2015) proposed a frosting map that helps to identify the most critical conditions for frost formation. In those conditions where frost can occur, the ambient temperature/relative humidity (UR) plane is divided into 4 zones, namely severe, moderate, mild or no risk of frosting. The approach proposed by Zhu and Sun has been applied in the simulation, and when the outdoor conditions fall into one of the risk zones, the heat pump performance is corrected by a degradation coefficient. The estimation of the degradation coefficient for each zone is based on the experimental results obtained by Chen & Guo (2009) on reverse-cycle defrosting of an air source heat pump. The paper presents the effects on the performances of the unit for a wide range of outdoor air temperatures and relative humidities.

Additionally, the implemented model accounts for performance derating during the heat pump startup phase. In this phase, the heat pump cycle operates at different conditions respect to steady-state operation. These deviations result in efficiency losses, that occur at each startup of the unit. For instance, Bagarella *et al.* (2013) described the phenomenon and performed experimental evaluation for the determination of the losses due to a chiller on off cycling. In a more recent work (Bagarella *et al*., 2016), the authors evaluated the effect of the heat pump sizing and on off cycling phenomenon on the annual energy performance of the system. In the present work a similar procedure was applied to take cycling losses into account. Based on the results reported in the literature, a penalty coefficient has been applied for the first transient period at each startup of the unit.

2.2 Building Demand Simulation

The model of the HHPS described in the previous paragraph has been applied in a DBS (Figure 3). The hybrid system serves the heating request of a DHW tank and a hot water tank devoted to space heating through a primary loop. The pump in the secondary loop is activated whenever there is a space heating request and, consequently, the thermostat signal is on. Heating and DHW supply temperature can be increased, if necessary, by electric backup heaters, which are used as integration only in the reference case, i.e. the only heat pump system, if the set point temperature is not reached. The timestep used in the simulation has been set to five minutes. The building that is taken as a reference is a single-family residential building, composed by two heating zones of approximately 90m^2 each.

2.3 Simulation Framework

Throughout the simulations different parameters have been varied in order to gain a comprehensive understanding of the efficiency of hybrid systems in different contexts.

- Simulations were run for two cities located in the north of Italy, Belluno and Reggio Emilia, presenting different types of climate. Belluno, with 3.043 heating degree-days (HDD_{20}) and a heating design temperature of -11°C, is taken as reference for the climate 'cold', while Reggio Emilia, with 2.560 HDD_{20} and a design temperature of -7°C, is taken as reference for the climate 'moderate'.
- Two different levels of building insulation were considered. The first one (B1) simulates a building that was built in Italy in the seventies, with a heating demand in the 'moderate' temperature (Reggio Emilia) of 140 kWh m^{-2}y^{-1}, while the second one (B2) simulates a building built in the nineties, with a heating demand in Reggio Emilia of 50 kWh m^{-2}y^{-1}.
  B1 is provided with low temperature radiators. In this case, the space heating water tank of 0.1m^3 is kept at a design temperature of 52°C and adjusted by an outdoor reset control (OTR). B2 instead is provided with radiant panels. In this case, the set point temperature of the space heating water tank is set at 40°C at the minimum ambient temperature and it is also adjusted by the OTR curve. The set point of the heat generator water supply is 3°C higher than the set point of the water tank.
- Two profiles of DHW demand have been simulated: the first one, called the 'L' profile, with a daily consumption of 0.25 m^3, the second one, 'XXL' profile, simulates a larger consumption: 0.55 m^3 per day. The DHW is provided at 45°C and the DHW tank is kept at a temperature of 55°C. The volume of DHW tank considered is 0.3m^3 for simulations with the 'L' profile, and 0.5m^3 for the XXL profile.

For each case that was mentioned, a series of simulations were run in order to determine the best temperature at which the logic switches between boiler and heat pump for SH (T_{switch_SH}). In addition, a series of simulations were run for the determination of the best temperature to switch between boiler and heat pump, in case of hot water demand (T_{switch_DHW}).

It has been checked that the simulations with different configurations and same set of parameters provided the equal amount of heat to the system and that the set points of SH and DHW have been fulfilled.

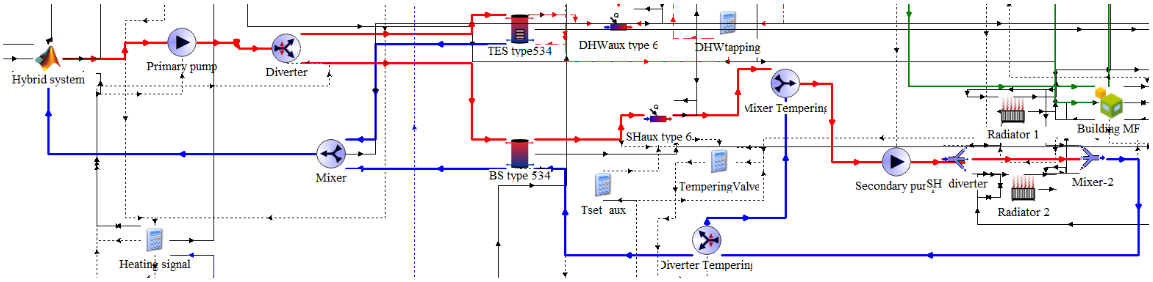

Figure 3: co-simulation layout

3. RESULTS

The simulations have been organized as shown in Table 1. 'Case 1' identifies the results obtained with the simulation of the less insulated building (B01), considering the colder climate and the DHW demand profile 'L'. Case number 2 identifies the results of the simulation for the same parameters, but in the moderate climate. Case number 3 and 4 instead, show the results of the simulations conducted for the newer and more insulated building, for the cold and moderate climate and DHW demand profile 'L'. Case number 5 and 6 compare the results obtained with the set of parameters of case 3 and 4, but with a larger profile of DHW demand (XXL).

For each case, the primary energy required by the heat pump (reference case) has been compared with the ones obtained by OS1 (Figure 1) and OS2 (Figure 2).

Figure 4 – Figure 6 show how T_{switch_SH} and T_{switch_DHW} have been determined. A series of simulations have been performed with different values of T_{switch_SH} and T_{switch_DHW} for the determination of the value minimizing the primary energy (P.E.).

Figure 4 shows the results for the cold climate (case 1 and 3). The simulation performed with building B1 provided with radiators showed an optimal T_{switch_SH} of 6°C, while the simulations with B2 and radiant panels showed an optimal T_{switch_SH} of 4°C. Similar results were obtained for the moderate climate (Figure 5). The reason for that can be found in the set point temperature of the system, that is lower when building B2 and radiant panels are applied. This leads to a lower optimal T_{switch_SH} of 4°C compared with 6°C, obtained with building B1 provided with radiators. A series of simulations with the only DHW demand determined T_{switch_DHW} for the L and XXL profile, showing an optimal value of 6°C in both cases (Figure 6). The same value of T_{switch_SH} determined in case 3 and 4 has been applied for case 5 and 6, as the set of parameters selected for SH is the same.

The heat pump size and the DHW tank have been adapted in order to obtain a similar performance of the configurations, i.e. to fulfil the heating and DHW setpoints in each configuration. The size of the DHW tank selected is 0.3m^3 for simulations with DHW profile 'L', and 0.5 m^3 for DHW profile 'XXL'. Due to the large modulation range of the boiler, only one boiler size was used.

Table 2 summarizes the results of the simulations for case 1 to case 6. It reports the size of the heat pump selected (Pref), at the standard working conditions of 35°C of supply water temperature and 7°C of ambient air temperature, as well as the savings obtained with OS1 and OS2.

To avoid a system oversizing, the reference case is provided with backup electric heaters. The heat pump is sized to cover at least 98% of the annual energy demand.

Table 1: Overview of simulation parameters

Case Number	Building type	Climate	DHW Profile	DHW/ total demand
1	B01	Cold	L	10%
2	B01	Moderate	L	12%
3	B02	Cold	L	25%
4	B02	Moderate	L	30%
5	B02	Cold	XXL	40%
6	B02	Moderate	XXL	46%

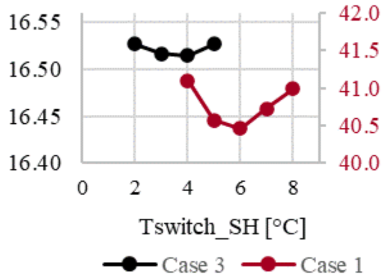

Figure 4: P.E. [MWh] of OS1 at different T_{switch_SH} for the cold climate (case 1 and 3)

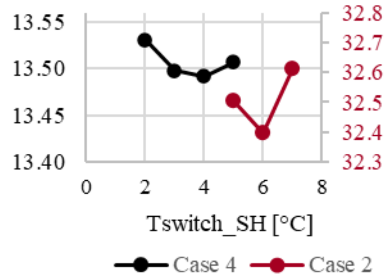

Figure 5: P.E. [MWh] of OS1 at different T_{switch_SH} for the moderate climate (case 2 and 4)

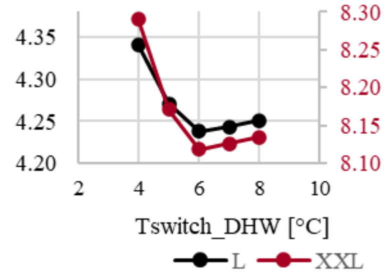

Figure 6: P.E. [MWh] for determination of the optimal T_{switch_DHW} (L and XXL profile)

Table 2: Heat pump capacity and primary energy savings in comparison to the reference case for case1- case 6

CASE 1	REF. CASE	OS1	OS2
Pref [kW]	28.5	13	20
P.E. saving	0.0%	29.6%	30.4%

CASE 2	REF. CASE	OS1	OS2
Pref [kW]	28.5	11	20
P.E. saving	0.0%	22.9%	24.1%

CASE 3	REF. CASE	OS1	OS2
Pref [kW]	25	8.5	16
P.E. saving	0.0%	9.2%	12.1%

CASE 4	REF. CASE	OS1	OS2
Pref [kW]	23	8.5	15
P.E. saving	0.0%	0.0%	4.6%

CASE 5	REF. CASE	OS1	OS2
Pref [kW]	30	8.5	25
P.E. saving	0.0%	9.8%	14.0%

CASE 6	REF. CASE	OS1	OS2
Pref [kW]	30	8.5	25
P.E. saving	0.0%	1.3%	6.5%

Case number 1 shows the results for the less insulated building provided with low temperature radiators, for the cold climate. The result of the comparison shows that the hybrid system can lead to 30% savings in terms of primary energy. In this case, the advantage of having a more complex control logic, i.e. OS2, leads only to small primary energy savings (+1%) compared to OS1.
Case number 2 provides the results for the less insulated building provided with low temperature radiators in the moderate climate. The savings that the hybrid system can achieve reach almost 25% with OS2. As in the previous case, the savings achieved with the OS2 configuration are approximately 1% higher compared to the OS1 configuration.
Considering case 3, the comparison between the reference case and the most favorable configuration of hybrid system (OS2) shows more than 10% of primary energy savings. The additional savings compared with the hybrid configuration OS1 reach almost 3%.
In case 4, the total primary energy required for the reference case is reduced compared to the previous case, as well as the savings that can be obtained through the application of a hybrid system. OS2 achieves savings of almost 5%, while no savings are achieved by OS1.
Case 5 and 6 see an increase of savings obtained with OS1 and OS2 compared to case 3 and 4, due to the application of larger DHW demand profiles. In case 5 the savings obtained with OS2 reach 14% and exceed of more than 4% the savings obtained with OS1. In case 6 the savings obtained with OS2 almost reach 7% and exceed of more than 5% the savings obtained with OS1.

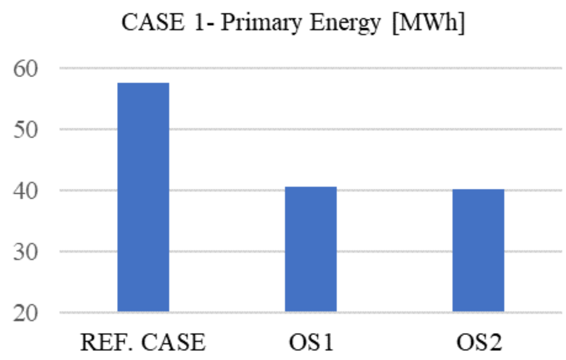

Figure 7: Comparison of primary energy consumption of heat pump only and two hybrid configurations- Results for case 1

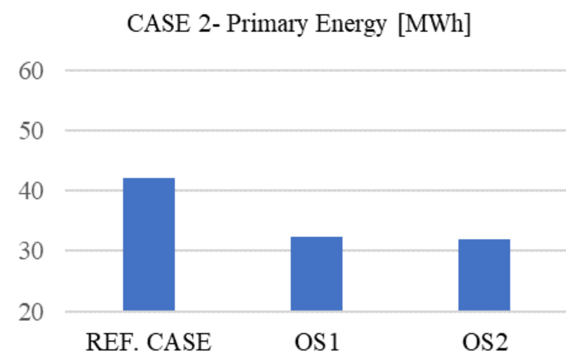

Figure 8: Comparison of primary energy consumption of heat pump only and two hybrid configurations- Results for case 2

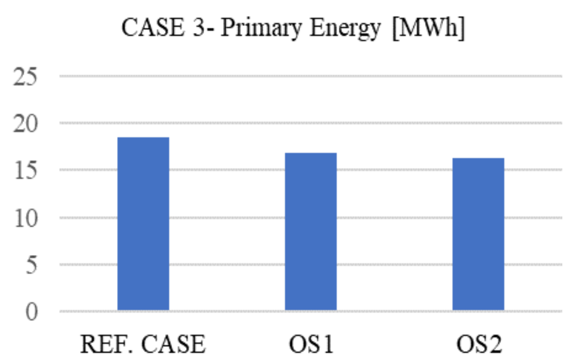

Figure 9: Comparison of primary energy consumption of heat pump only and two hybrid configurations- Results for case 3

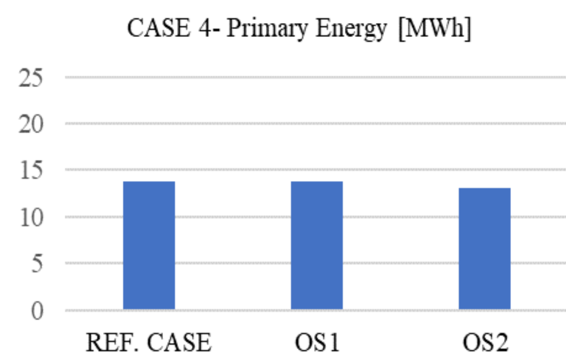

Figure 10: Comparison of primary energy consumption of heat pump only and two hybrid configurations- Results for case 4

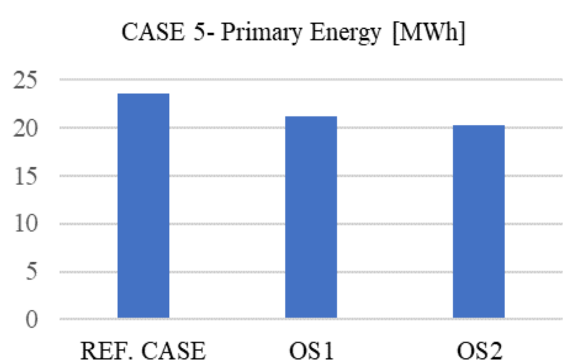

Figure 11: Comparison of primary energy consumption of heat pump only and two hybrid configurations- Results for case 5

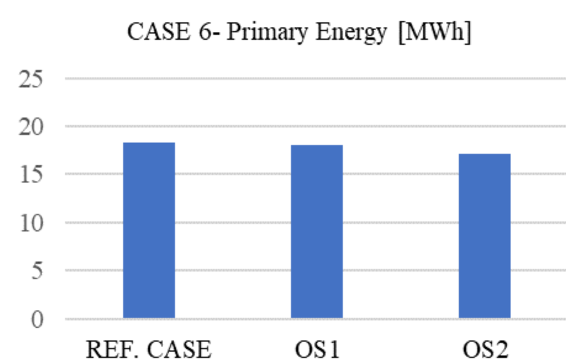

Figure 12: Comparison of primary energy consumption of heat pump only and two hybrid configurations- Results for case 6

3.1 Discussion

The six cases presented in the previous paragraphs show a high variance in the results, i.e. in the savings that the hybrid solution can obtain in terms of primary energy.

The hybrid solution shows remarkable benefits in those simulations involving the less insulated building provided with radiators, considering both the climate ‘moderate’, and even more the climate ‘cold’.

The comparison between the two configurations of hybrid system analyzed shows that the difference between the solution where a switch temperature is applied also to the DHW demand (OS2) and the solution where the boiler covers the total demand of DHW (OS1) does not differ substantially in terms of total primary energy consumption. This is true especially for low insulated buildings, where the savings between the two hybrid solutions are approximately of 1%. If the heat pump contributes to the DHW production, the implemented regulation required for the system is more complex and the size of the heat pump must be larger, which is probably not convenient if the saving is low. Moreover, if the heat pump is oversized compared to the space heating load, it will reduce the optimal functioning of the system, causing more frequent on-offs, thus affecting the performances and also the compressor’s life.

In the cases where the simulations have been performed with the higher insulation building provided with radiant panels (case 3 and 4), the portion of primary energy that can be saved with a hybrid system is reduced compared to the case of the building provided with radiators (case1 and 2), due to the lower energy demand of the building and the lower set point of the system, which is advantageous for the heat pump efficiency. Savings however reach 12% when the simulation is performed for the climate ‘cold’. The convenience of OS2 in comparison with OS1 increases as much as the weight of the DHW on the total energy demand increases (Table 1). This tendency can be seen in case 3 and 4, and especially in case 5 and 6, where the additional savings of OS2 respect with OS1 reach more than 5%.

According to these results, the hybrid solution has to be highly recommended in buildings that are provided with radiators. In refurbishments, radiators are rarely substituted with radiant panels, due to the large amount of work and high cost required. The usage of low temperature radiators gives the heat pump the possibility to reach the required supply water temperature and so to be integrated into the system. However, the heat pump only solution is not convenient in terms of primary energy demand. In a moderate or cold climate, as the ones considered in the simulations, there are many periods during the year in which the efficiency of the heat pump is reduced, due to the level of supply water temperature required. The low ambient temperature and the occurring of defrost cycles reduce the performances of the heat pump, while the boiler efficiency is not affected by external conditions. The boiler instead, at the supply water temperature levels considered for low temperature radiators, enhances its efficiency through condensation. Nonetheless, the application of a heat pump, properly integrated in a hybrid system, can reduce the primary energy consumption, and allows for the usage of a portion of renewable energy for the heating needs.

The exclusive operation of the boiler for the load of DHW (OS1), leads to the possibility of choosing a size of heat pump that suites best the building heating needs, avoiding an oversizing of the heat pump. An aspect that was not considered in the simulation but should not be neglected is legionella prevention. The boiler as backup generator gives the possibility to keep the DHW tank at a higher temperature level, or allows for operating cycles preventing legionella formation, in a more efficient way compared to the heat pump in combination with electric heaters.

Performing a cost evaluation of the proposed solutions is necessary to evaluate if the benefits in terms of primary energy savings are confirmed in economic terms.

4. CONCLUSIONS

The analysis described in the present paper has been conducted with the aim of identifying the convenience of the application of HHPS in terms of primary energy, by varying different parameters, such as building insulation level, type of heating terminal, DHW demand profile and climate.

To do so, a co-simulation of a hybrid system serving space heating and DHW demand of a residential building was developed.

The analysis has compared the results obtained by applying the hybrid system or the heat pump, for serving the demand of SH and DHW. Two different configurations of hybrid system were compared: OS1, in which the boiler provides the total DHW load, and the switch between boiler and heat pump for SH is determined by a pre-defined value of the ambient temperature (T_{switch_SH}); OS2, in which two temperatures of switch have been determined, one that is adopted when the system operates in DHW mode (T_{switch_DHW}), and one when the system operates in space heating mode (T_{switch_SH}).

Two levels of building insulations were compared, referring to buildings constructed in different ages. The less insulated one (B1) is provided with low temperature radiators, while the more insulated one (B2) is provided with radiant panels. Two cities in the north of Italy have been chosen as reference for a ‘cold’ and ‘moderate’ climate.
The results of the simulations show that the savings that can be obtained with the hybrid solution compared to a heat pump only solution, considering building B1, provided with radiators, range from 24% to 30%, for the moderate and cold climate respectively. What can be noticed is that the primary energy demand obtained with the OS1 exceeds that of the OS2 only by approximately 1%. Since the production of DHW requires higher heat pump capacities and more complex regulation, the most advisable solution in this case is OS1. Instead, when the ratio of DHW energy demand compared to the total energy demand increases, the convenience of the OS2 is increased compared to OS1. This is true in particular for case 5 and 6, where the savings of OS2 compared to OS1 increase up to 5%.
The savings that can be obtained with the application of hybrid systems in newer homes provided with radiant panels range from almost 5% to 12% for moderate and cold climates respectively.
The results of the simulations give a general view of the application of HHPS. Hybrid systems can be efficiently applied in renovations, where the heating emission system is not changed, and buildings are still provided with radiators. In this case, the installation of a hybrid system would lead to primary energy savings, and at the same time allows for the usage of renewable energy. If the boiler provides the DHW demand (OS1), the heat pump can be dimensioned to better suite the building needs. This configuration should be preferred when the ratio of DHW to total energy demand is low. The configuration in which the heat pump contributes to cover the DHW loads should be taken into consideration for large DHW/ total energy demand ratios.
This paper evaluated the performances of the configurations based on the primary energy consumption. The purpose of future studies is to include a cost evaluation, in order to have an overview of the most convenient solutions also in economic terms.
Moreover, the present study focused on the parallel configuration of the generators, which is the most widespread one at the moment. Future studies will consider the performance of different configurations of hybrid systems, such as the configuration in series.

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