CYTEF XII Congreso Ibérico y X Congreso Iberoamericano de Ciencias y Técnicas del Frio
Universidad Miguel Hernández de Elche
26-06 28-06/2024
UNIVERSITAS Miguel Hernández
DOI: 10.21134/n5qjem63

HAPPENING: an efficient cascade heat pump system for multifamily buildings

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Abstract: *An innovative hybrid heat pump system is presented as a novel solution for multifamily building heating system retrofitting. This system is very efficient on the one hand thanks to its innovative configuration in cascade, minimum thermal losses and on the other hand, the maximization of local solar energy self-consumption due to decoupling generation and consumption and applying smart control strategies. It is aimed at facilitating retrofitting of existing heating systems in multifamily buildings, enabling an efficient decarbonization. Three variations of the system have been designed, installed, and tested in real buildings across Europe, within the H2020 project "HAPPENING". The project is now under monitoring phase and the preliminary results are positive, demonstrating the high efficiency of the concept.*

Figure 1. Central part of the installation in a demonstration site (Pasaia, Gipuzkoa, Spain)

Keywords: Heat pumps, renewables, hybridization, efficiency, retrofitting.

1. INTRODUCTION

Heating and cooling accounts for about 50 % of the overall EU energy consumption [1]. Buildings (mostly residential) represent the highest share within that consumption, in fact, they are the single largest energy consumer in Europe and, approximately, the 80 % of the energy they use is for heating, cooling, and domestic hot water (DHW). Currently, most of that energy demand is covered by burning fossil fuels, which makes this building sector responsible for over one third of EU's energy-related greenhouse gas (GHG) emissions [2]. Even if more sustainable alternatives are favored by recent energy directives, this has a limited impact (on new buildings), as the building stock in Europe is mostly old and relying on conventional systems. Therefore, phasing out existing HVAC systems based on fossil fuels and replacing them with more efficient and sustainable alternatives is key to reach the overall climate protection targets defined by the European Commission. However, current renovation rates are still low, and solutions are needed in order to facilitate retrofitting aligned with this transition.
In this context, heat pumps (HP) are a key technology to efficiently decarbonize the thermal supply of buildings, as they are both much more efficient than conventional boilers and particularly good at bringing high shares of renewable energy self-consumption when hybridized with local clean electricity production (e.g., photovoltaics (PV)). For example, an average air/water HP in a typical single-family house in Spain entails a reduction of about 75 % in energy use and almost 80 % in carbon emissions in comparison with a conventional gas boiler [3]. As a result, in recent years a growing trend towards HP installation has taken place in Europe, partly because of the increase of gas prices in comparison to the cost of electricity. For example, in Spain there was an increase of 24 % in HP sales in 2022 compared to the previous year [3]. However, the installation rates in existing multifamily buildings are still marginal, as they represent less than 10 % of the total installations [4].

The lack of installations of HPs within existing multifamily buildings is due to several barriers, such as high temperature requirements by the emitters and high thermal losses in the distribution pipes. In order to overcome these barriers an innovative system concept is proposed, based on cascade heat pumps hybridized with solar energy. Thus, the system basically consists of two levels of temperature, with an energy storage in between plus local renewable energy production:

- Central air-to-water HPs cover a first thermal gap, maintaining water temperature constant at a low temperature distribution loop (around 20 ºC), which leads to high COP and minimum distribution thermal losses. Alternatively, depending on the local resource availability, the central air-to-water HPs can be replaced by a low-grade heat source, such as a low temperature district heating, a solar thermal installation, etc.
- The central HPs are also connected to a thermal energy storage (TES), which allows to decouple generation and consumption and enables storing locally produced solar energy for later use. This also provides flexibility to use of the central HPs during the hours of the day when their performance is highest, which usually coincides precisely with the peak production of the PV. Smart control strategies are applied in order to maximize the utilization of these possibilities, enhancing the overall efficiency of the system.
- At dwelling level, individual water-to-water or water-to-air HPs cover each particular heating, optionally cooling, and DHW demands, obtaining optimized demand response adjusted per user and enabling the use of different emitters for each dwelling. These individual HPs have also a very high and constant efficiency as they are fed by the intermediate water loop. A variety of emitters is possible.

This concept has been demonstrated within the HAPPENING H2020 project in 3 demonstration sites across Europe (Spain, Italy and Austria). The scalability and adaptability of the system has been proved as the system has been installed with different configurations and equipment in buildings different in size (8, 10 and 18 dwellings, respectively) and covering variable energy demands corresponding to different climates and regulations.

2. METHODOLOGY AND DESIGN

In this paper we focus on the design and results of one of the 3 demo sites, the one located in Pasaia (Gipuzkoa, Spain). Therefore, in the following sections it is described in detail. However, some mentions are included about the 2 other demos in order to illustrate the different possible HAPPENING solution particularizations aimed at adapting to specific requests defined by case-specific restrictions, such as weather, demand profiles, user preferences, local regulations, etc. Based on those, the methodology applied for the system design was the same in all 3 demos:

1. Energy demand assessment: to define the thermal capacity of the new system, the characteristics of the building were analyzed, as well as historical energy consumption data, which was gathered from energy bills provided by the users. Thermal energy demand data was used to size the new HP system and electric consumption, available at hourly basis from the electric smart meters, was used to size the new PV system. As a result of this analysis, it was concluded that the cooling demand was negligible in Pasaia and thus the system is optimized for heating and DHW production. In the Italian demo, for example, there was indeed a demand for cooling which was not addressed with the existing installation, and thus the new system was designed to also provide this service and thus improve the thermal comfort of residents.

2. Current system assessment: it is key to look for potential reutilization of existing elements in order to facilitate the retrofitting work and reduce its impact in terms of both installation effort and economic cost. In the case of Pasaia, the existing system consisted of individual gas boilers with conventional radiators as emitters. There was also a solar thermal installation which was unused and posed an interesting potential to reutilize some elements, such as the hydraulic distribution pipes and an individual water buffer tank already present in each dwelling. As a result of the reutilization assessment, the existing distribution piping was discarded due to its dimensions, since the new system implies water distribution at low temperatures (around 20 °C), which requires higher mass flow rates than in conventional high temperature configurations, and thus the resulting velocities would have been too high for the existing pipes (not designed for such purpose). The reutilization of the water storage tank corresponding to the old solar thermal installation was discarded too, due to the uncertainty about its physical condition after 15 years without use and the fact that a water-to-water HP with a built-in DHW tank was a more compact solution. As for the emitters, there were relatively new double steel panel radiators, suitable for their use under HP production temperatures, it was decided to keep them in order to reduce the cost of the intervention and the impact of the works at dwelling level on the tenants.
   In the Italian demo, the existing system was quite different: central boiler both for DHW and heating through fancoils. In this case, the presence of a relatively low temperature distribution made it possible to reuse all the hydraulic distribution system. As for the emitters, the presence of fancoils and its auxiliary elements already in place (drains, etc.) enabled the replacement with water-to-air R290 microHP producing both heating and cooling.

3. New system detailed design: in Pasaia (see schematic diagram in Figure 2), two R290 air-to-water HPs were installed as central HPs connected to a TES (see Figure 1). The number of units was defined based mainly on power requirements, but also considering redundancy as an additional benefit to the system in terms of security of supply. As for the refrigerant, R290 was favored due to its low global warming potential (GWP) and wide range of production temperatures, enabling enhanced thermal accumulation of surplus renewable electricity from the 15 kW PV installation present on the roof.
   The central buffer storage tank was sized at 2000 l based on thermal capacity and space availability in the parking in which the central installation is located. In parallel to this thermal energy storage, an electric accumulation capacity is installed, with 14.4 kWh batteries. These storages enable decoupling energy generation and consumption and allow for high renewable electricity self-consumption rates, minimizing imports from the grid which result in savings both in costs and emissions.
   Independent of the tank temperature (which could be increased through the HPs to consume surplus electricity), distribution temperature is kept constant by a three-way-valve that mixes the outlet from the central buffer tank with the return from dwellings to maintain supply temperature at 19 °C. This temperature was selected as it minimizes thermal losses and maximizes individual HPs' COP, while still retaining proper refrigeration cycle regulation capacity through the expansion valve.
   Regarding heat emitters, as mentioned, existing radiators were kept and thus R290 water-to-water HPSs were selected due to their capability of producing hot water up to 70 °C. However, it was later proved that adequate heating was possible even with production temperatures below 60 °C. These water-to-water HPs are originally designed as geothermal HPs and thus already include a circulating water pump, not only at production side but also at the primary source side. Therefore, there was no need for dedicated water pumps in the distribution and the installation was properly hydraulically balanced thanks to an reverse return configuration.

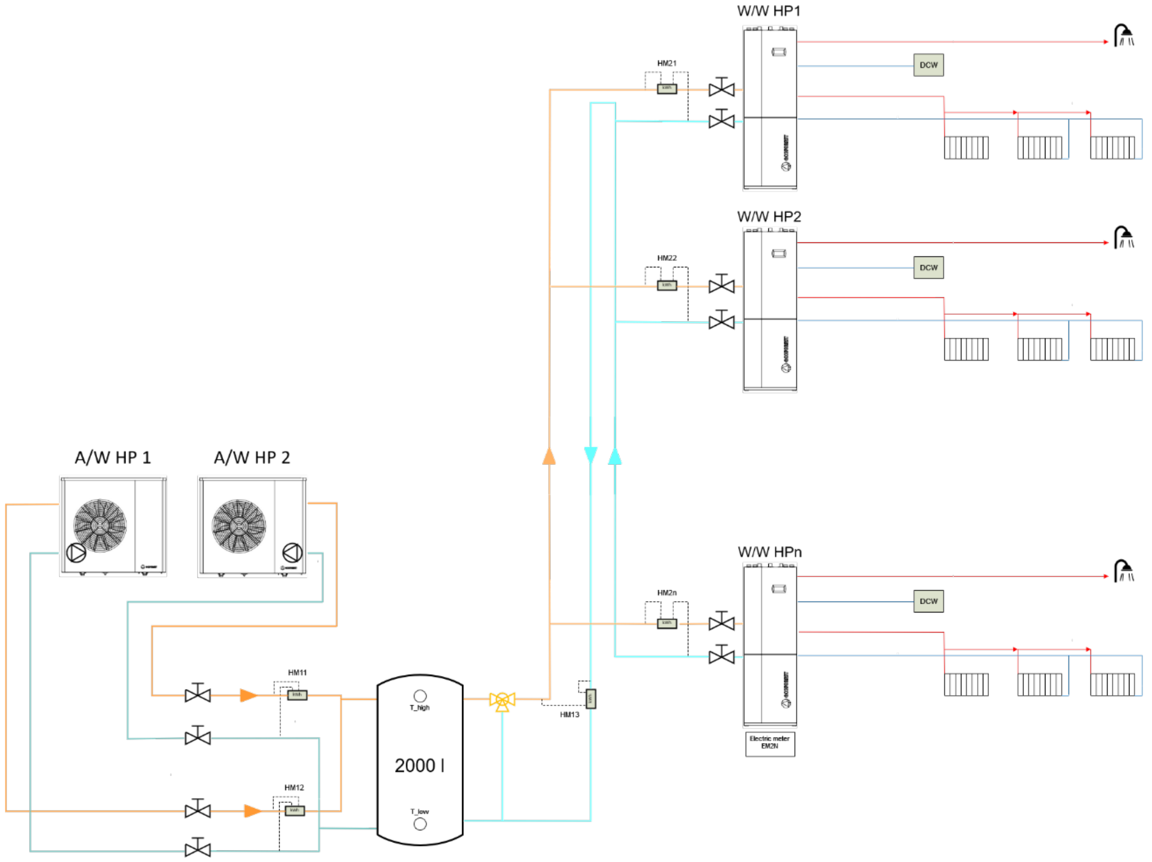

Figure 2. HAPPENING system thermal layout in Pasaia demo site

3. RESULTS AND DISCUSSION

It is worth noting that, as of this writing, the monitoring period of the demo installations has not been completed and thus the results shown in this chapter are partial, mainly corresponding to the last heating season.

The results of the system are evaluated through several key performance indicators. Among those, HP performance factor is key to assess such a cascade HP system. The average results of both central air-to-water HP and individual water-to-water HP are shown in Figure 3, as well as the combined performance factor, which is defined by equation 1. A/W HP performance is clearly dependent on mean outdoor temperature: lower in colder winter modes, but outstanding regardless, due to the low ΔT between source and production (buffer tank temperature setpoint = 25 °C when no surplus available). W/W performance, in contrast, remains almost constant due to the fact that the distribution water loop temperature is controlled and kept at 19 °C.

$$COP_{tot} = \frac{COP_1 \cdot COP_2}{COP_1 + COP_2 - 1} \quad (1)$$

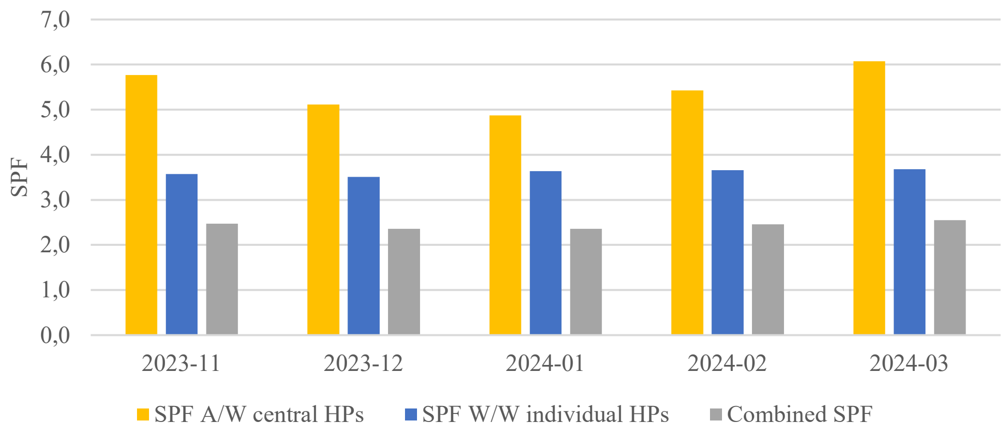

Figure 3. HAPPENING HP average monthly performance factor

Based on monitored energy consumption data, we can evaluate the improvement provided by the new HAPPENING system over the substituted gas boiler system. Given the performance rating of the old boiler (efficiency of 91.3 % at 100 % load according to manufacturer catalogue data), we can estimate the natural gas consumption expected, in the same conditions as in the monitoring period, as the thermal load in the period divided by the boiler efficiency. As for the electricity consumption for non-thermal uses we can assume that it would have been with both systems, and we can thus evaluate the performance of the refence system (same electric consumption for regular appliance consumption but gas for heating and DHW).

The Figure 4 shows the results of the comparative analysis in terms of GHG emission savings in monthly basis for the HAPPENING system and the reference system, which yield monthly savings in the range of 63-72 %, depending on the ratio of thermal and electrical loads for each month:

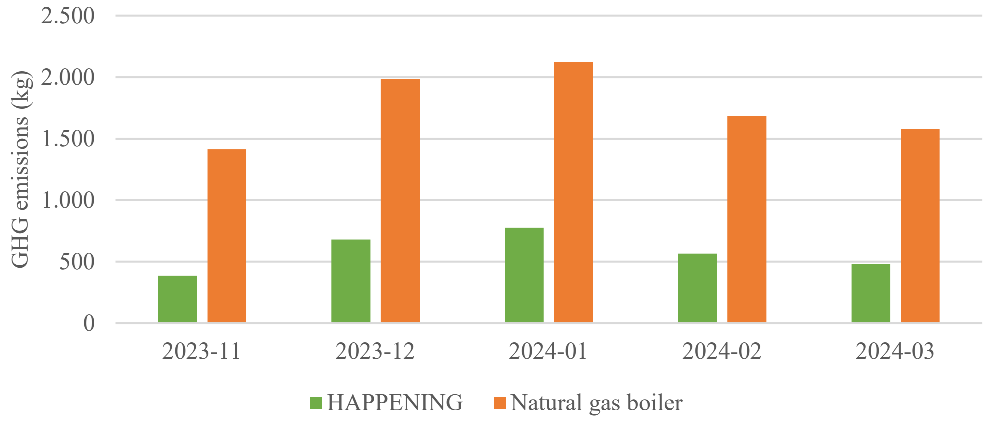

Figure 4. HAPPENING system VS natural gas systems in terms of GHG emissions

A similar analysis in terms of primary energy (PE) consumption is shown in Figure 5:

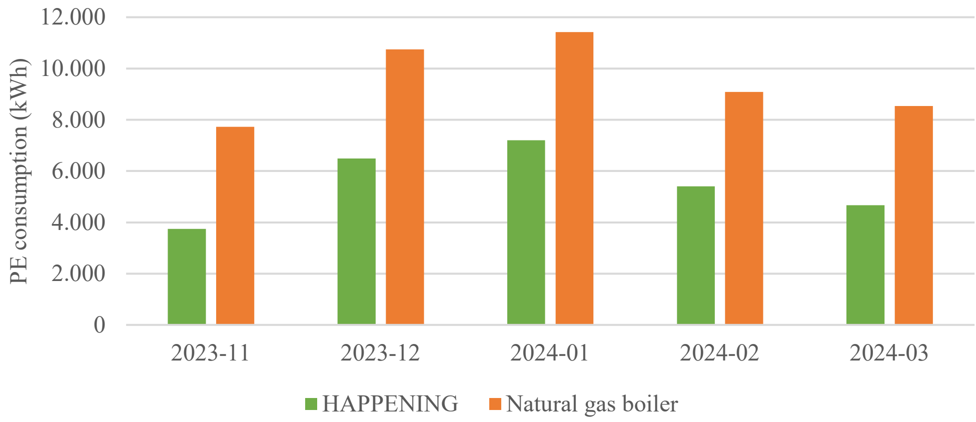

Figure 5. HAPPENING system VS natural gas system in terms of PE consumption

There is a reduction in total primary energy consumption, that ranges between 40-50%, caused by the use of local energy sources (air) with low PE content, as well as the overall efficiency of the system, which provides an improvement with respect to the reference system efficiency by a wide margin, enough to overcome the high PE content of the electricity consumed. The shift motivated by the air use affects not only the PE consumption, also the non-renewable fraction of the PE, as shown in Figure 6: while the reference gas boiler system PE consumption is mainly non-renewable, the new HAPPENING system is able to provide higher renewable PE energy. Thus, not only it reduces the total PE consumption, but also increases the renewable share, as shown in Figure 6. These results are expected to become even better for the HAPPENING system with the introduction of the locally produced renewable energy fraction, as soon as the solar PV system is started (currently pending because of administrative procedures).

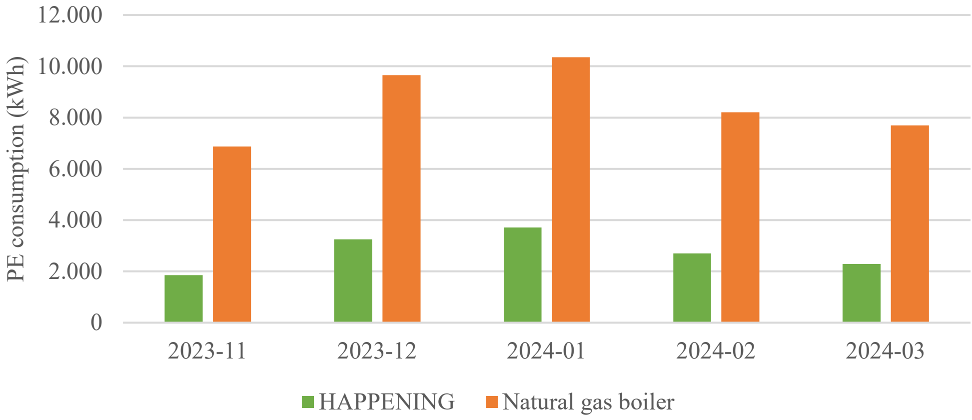

Figure 6. HAPPENING system VS natural gas system in terms of non-renewable PE consumption

4. CONCLUSIONS

The following points summarize the main features and benefits from the presented HAPPENING solution:

- As the heat generation is decoupled from consumption, thanks to the 2 levels of generation separated by the TES, the smart controls can optimize the COP of the central HP and maximize the consumption of locally generated renewable energy, for example storing hot water in the central hours of the day.
- Thermal losses in the water distribution loop are drastically reduced thanks to the low temperature setpoint (around 20 ºC).
- The COP of the individual heat pumps is high and constant, and they operate under steady conditions throughout the year, due to controlled water loop distribution temperatures.
- HAPPENING is a highly versatile solution for the refurbishment of the heating systems in multifamily buildings, as each single dwelling can decide the configuration that better fits their needs and interests among a variety of options, from the installation of a water-to-water HP for both heating and DHW generation to, e.g., a more complex and efficient configuration comprising a smaller water-to-water HP for DHW and water-to-air micro HPs in each room for heating and cooling.
- Finally, HAPPENING is a easily scalable system, as demonstrated thanks to the 3 demo sites in the project, which differ in size, climate, user needs and local norms and regulation.

The next steps will be to finalize the monitoring period, assessing the performance of the system under different demand conditions, such as cooling needs. In the particular case of Pasaia, the overall performance and economic results are expected to improve when the PV installation comes into operation.

5. ACKNOWLEDGEMENTS

This system has been developed within the European project “HAPPENING” with funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 957007.

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