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Evaluation of hybrid heat pumps' efficiencies and operating behaviors in collective dwelling buildings using a hardware-in-the-loop approach

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Abstract

Given the current climate change scenario and the growing global awareness of energy consumption and heat generation, many European stakeholders are advocating for complete electrification and extensive building renovations. However, implementing these measures takes considerable time due to various constraints. Meanwhile, many households remain uninformed about existing technologies and strategies that suit their financial, geographical, and housing conditions. Combining an electric heat pump with a boiler, either as a new hybrid heat pump system or as an add-on solution, offers the benefits of both technologies, including thermal power, reduced impact on electricity peak load, and improved overall efficiency.
This study focuses on evaluating the seasonal efficiency of commercially available hybrid heat pump using a Hardware in the Loop (HiL) approach. This method assesses equipment performance under real-world conditions. The heating season is condensed into 5 days using the k-medoid method for the Strasbourg climate region. The HiL system is connected to a climatic chamber that simulates external temperature and humidity. Heating needs are modeled using dynamic modelling software. A HiL experimental study was conducted on a typical collective dwelling with two insulation levels, and the seasonal efficiency of the system was computed. The results show that for both cases, low and high insulation levels, hybrid heat pumps offer good results and decreased fossil fuel reliance, highlighting this product as a flexible and effective tool for decarbonizing the heating sector.

Keywords: Hardware in the loop; k-medoids; hybrid heat pump;, seasonal efficiency; control strategies; electric heat pump.

1. Introduction

In the context of accelerating climate change and the European Union's ambitious decarbonization targets, reaching net zero carbon by 2050 [1], the building sector has emerged as a central focus for reducing greenhouse gas emissions.

The building sector accounted for 30% of the total global energy consumption in 2021 [2], nearly 50% of the EU's final energy consumption, with a significant share still reliant on fossil fuels, and nearly 41% of the total final consumption in 2020 in France [2]. To address this, European policymakers are actively promoting decarbonization of heating systems, mainly through electrification of heating systems and deep renovation of the building stock, as outlined in the revised Energy Performance of Buildings Directive (such as the French building environmental regulation RE2020) and the REPowerEU plan. However, the rate of implementation is constrained by technical, economic, and social barriers, particularly in existing poorly insulated buildings and traditional heating systems [3].

Hybrid heat pumps (HHPs), which combine an electric heat pump with a condensing boiler and a smart control system, have been identified as a promising technical solution, especially in climates and buildings where full electrification is not yet feasible. While stand-alone electric heat pumps can achieve high

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efficiencies, their performance strongly depends on outdoor climate, building thermal quality and heat distribution systems. In cold climates, efficiency drops at low outdoor temperatures, coinciding with peak heating and electricity demand, while many existing buildings - particularly older collective dwellings - exhibit high heat losses and rely on high-temperature radiator systems that are poorly suited to full electrification without extensive renovation [4]. HHPs address these constraints by dynamically combining electric and combustion-based heating, allowing them to operate at all outdoor and water inlet temperatures, in all types of buildings. This makes HHPs particularly suitable for decarbonizing older buildings, with poor insulation, without requiring immediate simultaneous upgrades to the building envelope and the heat distribution system [3].

Despite their potential, the real-world performance of hybrid heat pumps remains underexplored, particularly under dynamic operating conditions. Static laboratory testing in conventional mode often fails to capture the complex interactions between equipment, control strategies, and building thermal behavior. To bridge this gap, Hardware-in-the-Loop (HiL) simulation has emerged as a powerful methodology for evaluating HVAC (Heating, Ventilation and Air Conditioning) systems under real operating conditions. HiL integrates physical components with virtual building models, enabling real-time testing of control strategies and system responses to various climatic and load scenarios [5], [6]. Therefore, this study employs a HiL approach to assess the seasonal performance and operating behavior of a commercially available HHP system. The heating demand of a representative collective dwelling in the Strasbourg region is modelled for two insulation levels. The HiL system is coupled with a climatic chamber to reproduce outdoor conditions, allowing realistic testing of the hybrid unit under varying loads. To reduce testing time, the heating season is condensed into five representative days using the k-medoids clustering algorithm, a robust method for time series classification that minimizes sensitivity to outliers [7].

By combining experimental testing with advanced dynamic modelling, this work aims to provide insights, evaluate seasonal efficiency and study operational behavior of hybrid heat pumps in near-real-world applications. This semi-virtual setup enables the evaluation of both seasonal efficiency and operating behavior (distribution of heat pump and boiler operation) under realistic climatic conditions.

This study focuses on a collective dwelling scenario, and the impact of HHPs installation before and after undergoing a renovation scheme for space heating (Domestic hot water was not considered in this study and was assumed that a dedicated generator ensures the production). The results show that HHPs are products contributing to the decarbonization of the building sector focused on the end-user comfort.

2. Methodology and Assumptions

To simulate the building response, the building envelope is modelled based on the Modelica buildings library developed at Berkeley [8]. The building is assimilated to three thermal zones: first floor, top floor and intermediate floors. The building's surface area and walls' thermal resistances are those of a typical small collective dwelling and extracted from the ENERTER database [9]. The building is composed of 13 apartments, representative of the French collective housing. Each apartment has 3 rooms with a 63.7m^2 surface area.

Two building configurations are emulated to capture the influence of building envelope on heating demand:

- Non insulated collective dwelling, with thermal losses estimated at 76 kW at -15°C (The sizing temperature of the Strasbourg region).
- Insulated collective dwelling, with thermal losses reduced to 46 kW at -15°C

The thermal convection coefficient of each component of the building envelopes is detailed in the table below:

Table 1. U-values for the building envelopes

	U-value (W/m².K)	
Component	Non insulated	Insulated
Walls	1.84	0.54
Flooring	2	0.24
Ceiling	0.22	0.174
Windows	3	1.4

In this work, a commercially available HHP, using R290 as a working fluid, is used. The sizing of the electric heat pump of the HHP followed the rules developed by ENGIE Lab CRIGEN and detailed in [10]: the optimal point of the delivered thermal power, for the studied region, was found around 35% of the base load at operating temperatures of A0°C/W50°C. The HHP was sized based on the low insulated building load, in order to evaluate the impact on the heating demand before and after undergoing insulation works. The HHP, available on the market, that fits the sizing rules is composed of an installation of two electric HPs (Figure 3), sized at 40% of the base load at 0°C/50°C, and a gas boiler, sized at 100% of the heat load, coupled with a smart controller.

The hybrid configuration uses a bivalence temperature (T_{biv}) control strategy: it is the temperature that equals the theoretical load of the building to the heating capacity of the electric HP. Below T_{biv}, the gas boiler is authorized to start to match the heating load of the building (Figure 1[11]).

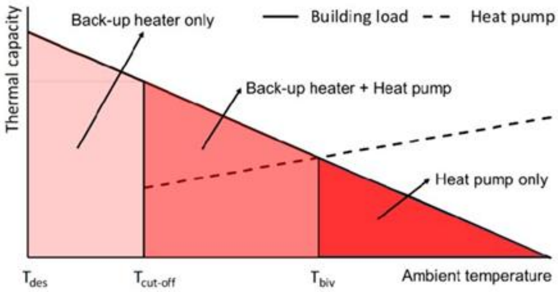

Figure 1. Bivalent temperature control strategy.

T_{biv} was fixed based on the manufacturer's recommendation, which highly depends on the size of the HP with respect to the total load (Table 2). The temperature below which the electric heat pump is automatically turned off (T_{Cutoff}), is fixed at -7°C (with respect to the manufacturer's recommendation and field installations).

It is also assumed that the radiators of the building are high temperature radiators, meaning that their nominal temperature is 70°C for the non-insulated building and 60°C for the insulated one. The heating curve was chosen accordingly (Supply temperature of 70°C and 60°C respectively for non-insulated and insulated buildings at -15°C). The indoor setpoint temperature is fixed at 19°C, the default temperature fixed in the French thermal regulation [12], with a fixed flow rate on the building part. The calendar year was reduced to 5 days, representative of the heating season, using the k-medoid method applied to the climate region of Strasbourg. The k-medoid clustering method consists of applying a clustering algorithm that divides a weather profile dataset into different clusters, each represented by a medoid—a data point within the cluster that minimizes the sum of dissimilarities to all other points in the cluster. In this work, the total heating season of the Strasbourg region was reduced, by minimizing the gap between the temperature and relative humidity of the medoid and the rest of the points. Each medoid is then weighted to represent the size of its cluster to maintain representativeness. Naturally, extreme cold days are smoothed out when reducing the total sequence, underlining the purpose of this approach to evaluate the seasonal performance of the product. The k-medoids algorithm is robust to outliers and noise, since medoids are actual data points within the dataset [7]. This helps reducing computation time. The overall reduction results in a 5-day short weather sequence instead of a total heating season. Figure 2 shows the outdoor temperature and relative humidity during this 5-day period. The sequence result gives an external temperature variation between -2°C and 14°C. The cut-off temperature was not reached in this sequence, as it is a result of the optimization algorithm.

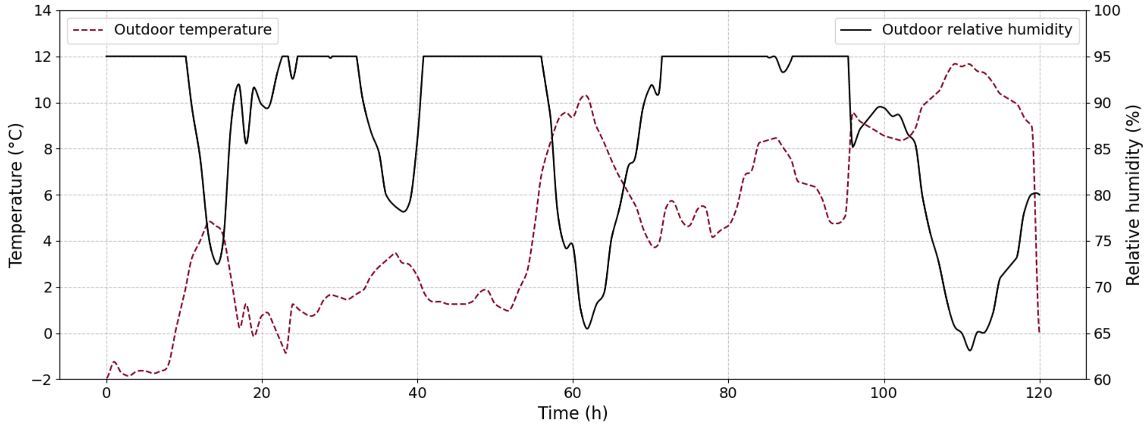

Figure 2. Outdoor temperature and relative humidity during the 5-day reduced calendar year.

At each time step, the simulated heating demand is converted into a hydraulic thermal load and applied to a test bench that is equipped with sensors for data acquisition. This test bench is connected to the heat generator, which is the HHP. The external unit of the HHP is placed inside the climatic chamber, where external climatic conditions (temperature and humidity) are reproduced. The HHP's ambient temperature probe is placed inside the chamber conditions to ensure the generator operates according to its heating curve. The hydraulic installation respects the manufacturer's recommendations as shown in Figure 3.

Table 2. Study Assumptions and heat pump specifications.

	Non insulated	Insulated
Bivalence temperature (°C)	7	-1
Building load (kW)	76	46
Specific heating demand (kWh/m^{2}a)	122.34	59.37
Ratio of installed power at 0/50°C / load (%)	40.4	66.7
Heat pump specifications		
COP A7°C/W35°C	4.3	
Heating capacity at A7°C/W35°C nom/max [kW]	14.3 / 18.7	
COP A7°C/W55°C	2.8	
Heating capacity at A7°C/W55°C nom/max [kW]	11.5/12.6	
COP A7°C/W65°C	2.3	
Heating capacity at A7°C/W65°C nom/max [kW]	9.6/10.4	
η_S at 55°C	143%	

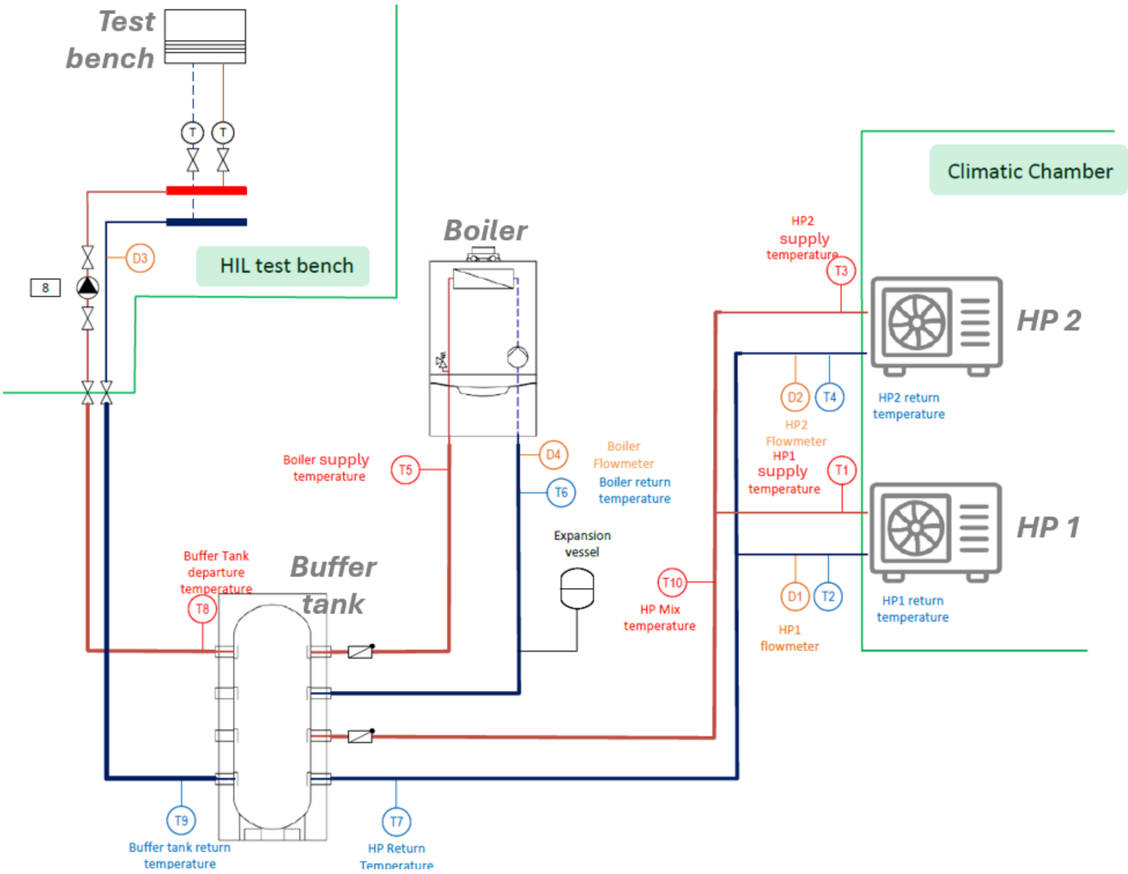

Figure 3. Hydraulic installation.

3. Equations

The added instrumentation as shown in Figure 3 allows us to monitor all the data necessary for the energy balance and the evaluation of the seasonal efficiency of the system (Eq. (1)) as well as the heat ratio covered by the electrical HP of the HHP (Eq. (2)). The seasonal coefficient of performance (SCOP) quantifies the overall energy efficiency of the hybrid system over the representative heating season, taking into account both the electrical and gas inputs, weighted for real-world operating conditions. The heat ratio (R) indicates the fraction of the total heating demand met by the electric heat pump, providing a direct measure of the system's reliance on renewable electricity versus fossil fuels.

$$SCOP_{C1} = \frac{\sum W_i \int [(\dot{m}_1+\dot{m}_2)C_p\Delta T_{10\text{-}7}+\dot{m}_4 C_p \Delta T_{5\text{-}6}]\, dt}{\sum W_i \int (P_{elec\ \text{-}HP1}+P_{elec\ \text{-}HP2}+P_{elec\ \text{-}boiler}).PEF+P_{gas\ \text{-}boiler}\, dt} \quad (1)$$

Where
W_i is the weight of each day of the 5-day sequence
$\dot{m}_1, \dot{m}_2 \& \dot{m}_4$ are the mass flow rates respectively for heat pump 1, heat pump 2 and the boiler (kg/s)
ΔT is temperature difference (°K)
C_p is the thermal capacity of water equal to 4180 J/(kg.K)
P_{elec} is the electrical power (W)
P_{gas} is the consumed gas power in (W)
PEF is the primary energy factor for electricity, equal to 2.3 in 2025 in France [13].

$$R = \frac{HP_{generated\ energy}}{HP_{generated\ energy}+Boiler_{generated\ energy}} \quad (2)$$

Where R is the heat ratio covered by the electrical heat pump.

4. Main results and Discussion

The main results of this work are detailed in Table 3 and Figure 4 Figure 5. The SCOP of the system is computed in primary energy (PE) and in higher heating value (HHV).

Table 3. HHP performance indicator.

	Non insulated	Insulated
HP-generated Energy (MWh)	66.2	40.3
Boiler -generated Energy (MWh)	22.2	0.8
Total Energy delivered to the building (MWh)	88.4	41.1
HHP SCOP (Primary Energy – HHV)	1.15	1.36
R	75%	98%

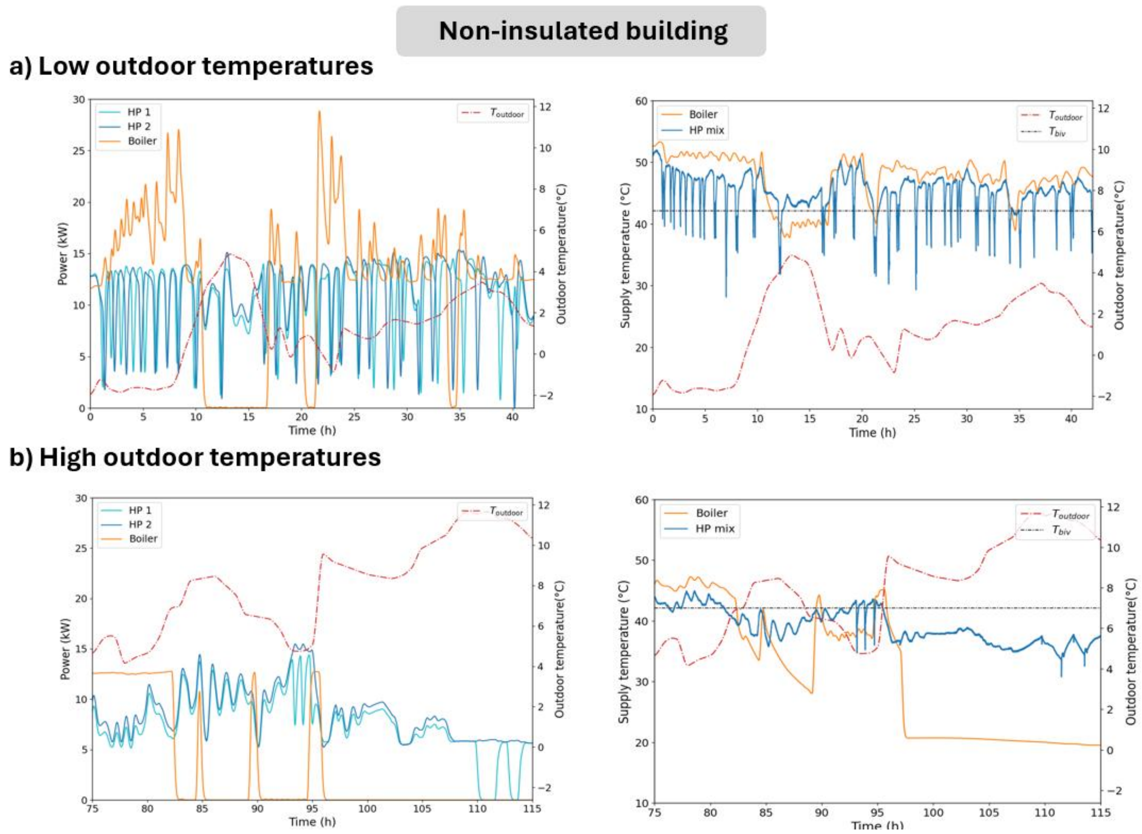

Figure 4. The power supplied by each component of the HHP and the corresponding supply temperature for a) low outdoor temperatures and b) high outdoor temperatures, for a non-insulated building.

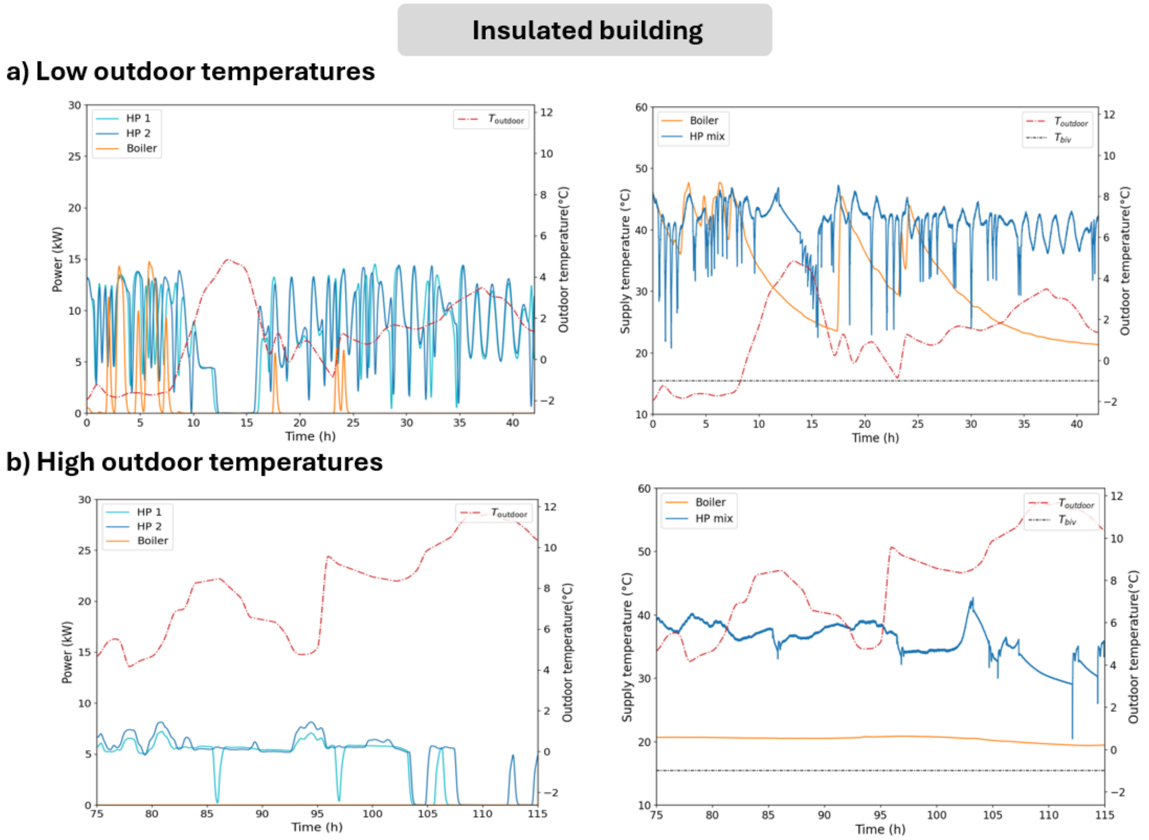

Figure 5. The power supplied by each component of the HHP and the corresponding supply temperature for a) low outdoor temperatures and b) high outdoor temperatures, for an insulated building.

In the **non-insulated dwelling (**Figure 4**)**, the installed power of the HP represents about 40% of the total thermal load at design conditions. As a result, the bivalence temperature is +7°C, which authorizes boiler operation below this temperature. Hence, over the represented heating season, the HP covers up to three-quarters (75%) of the seasonal heating needs (Table 3). Figure 4a shows the behavior of the system at **low outdoor temperatures** ($T_{outdoor} < 5°C < T_{biv}$) : The electric HPs run in priority as a base load, delivering around 28 kWth. The heating capacity of the HP being lower than the total load, the boiler runs to meet the demand, reaching 30 kWth, ensuring that total heat load is met (nearly 60 kWth). Similarly, the HPs are unable to meet the supply temperature setpoint, especially since the heating capacity is reduced at lower temperatures. The quick response of the boiler and its ability to lift the supply temperature by more than 5°C and the heat supply of up to 25 kW highlights the importance of the HHP, where both systems work in conjunction to maintain comfort. In contrast, at higher outdoor temperatures (Figure 4b), where $T_{outdoor} > T_{biv}$, the boiler is not authorized to work, and even, the electric HPs are able to meet all the heating load : The supply temperature of the HPs meets the heating curve and the delivered heating capacity is enough for maintaining comfort. Both scenarios, highlight the flexibility offered by the HHP, where at milder temperatures, the electric HP is enough, thus reducing the carbon emissions of the total system, while at colder more extreme temperatures, the boiler supports the system, therefore reducing the need for oversizing the electric HP and mitigating electricity peak loads, in low insulated energy consuming buildings. Over the total season, the system has a SCOP of 1.15 in [PE;HHV]. Note that this obtained SCOP for the non-insulated building is close to the value reported in [14] (1.10 in PE HHV) for a multifamily house in Germany, indicating a consistent performance trend of HHPs under similar building conditions and supporting the consistency of the present results.

In the **insulated dwelling (**Figure 5**),** where the same installed system represents a much larger share of the required load (≈67%), the total heat load decreases due to insulation improvements while the heating generators remain unchanged. This assumption puts forward the response of the same system after renovating the building envelope. Consequently, the bivalence temperature shifts down to –1°C, meaning the boiler is only needed during extreme cold events. This leads to a much higher coverage rate of 98% (Table 3), with the HPs supplying nearly all the heating demand. The SCOP in this case increases to 1.36 [PE;HHV] (Table 3). As shown in Figure 5.a, the gas boiler remains mostly inactive, particularly during periods of moderate outdoor temperatures, as the heat pumps alone can efficiently meet the reduced heating demand. For this case, when the outdoor temperature drops below T_{biv} (–1°C), the boiler intervenes and supplies the needed water temperature (Figure 5a.); and when $T_{outdoor}$ increases and surpasses the bivalent temperature (higher than 0°C), the HPs alone supply the heating demand with supply temperatures ranging between 35°C and 45°C. This behavior confirms that building renovation not only reduces the absolute heating demand but also enables lower supply temperatures while maintaining comfort, keeping thereby the boiler use for emergencies and extremely low temperature episodes, and improving overall system performance and energy efficiency. To the knowledge of the writers, no similar work has been done using the HiL approach over testing efficiencies of hybrid heat pumps for collective dwellings' space heating in the Strasbourg region of France, using a sequence reduction. However, when comparing the measured SCOP of the HHP to the η_s of the HP itself (Table 2), it shows close results especially in the insulated building (where a coverage heat ratio is nearly 100%). Although ηs is given at 55°C, the tested results give more precision as the sequence tested represents the total heating season (cold and mild days) following a heat curve reaching up to 60°C supply temperature. This is more accentuated in the non-insulated building, where higher temperatures are asked from the generator and the boiler is functioning to maintain comfort. Considering all, the performance of the HHP remains interesting in both cases, before and after renovation, where a significant reduction in CO_2 is possible, especially in buildings where total renovation is costly or impossible. The general findings of this work are coherent with those of [14] where the application of a HHP is an immediate measure to significantly reduce the emissions with low investment costs, compared to a building renovation.

5. Conclusion

This work analyzed the performance of HHP systems in both non-insulated and insulated collective dwellings, with emphasis on the operational behavior in near-real-world conditions. Experimental testing was combined with advanced dynamic modelling to assess the operation of the electric HP and boiler across varying climatic conditions and analyze the effect the renovation on system performance.

Results have shown that in the base case, corresponding to the non-insulated building, the hybrid system operated according to its design parameters: The electric HP covered the base load as a priority, while the gas boiler intervened only when the demand exceeded the heat pump's capacity. Under these conditions, the coverage ratio reached approximately 75%. This indicates that even with a relatively small heat pump, the hybrid configuration can substantially reduce gas consumption and contribute to decarbonization, while maintaining comfort, even in non-renovated buildings. Following renovation, the total heating demand decreased significantly, enabling the same hybrid heat pump to supply nearly all of the required energy with minimal reliance on the boiler. This underlines the dual advantage of hybrid systems: they provide immediate reductions in fossil fuel use in existing building stock, while simultaneously maximizing renewable energy coverage after renovation, thereby reinforcing their role as a flexible and effective tool for decarbonizing the heating sector.

6. References

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