15TH IEA HEAT PUMP CONFERENCE
MAY 26–29, 2026 | HOFBURG
VIENNA 2026
DECARBONISATION THROUGH INNOVATION

Impact of electric heat pumps size in a hybrid heat pump: a simulation and experimental sensitivity study

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Abstract

Hybrid Heat Pumps (HHPs) are a combination of an electrical heat pump, a gas condensing boiler and a smart controller. They are considered as a decarbonization product, able to reduce significantly CO_2 emissions. The size of the electric heat pump of the HHP has a big impact on the heat coverage rate supplied by the HP. This work conducts a sensitivity analysis of the HP's size in the HHP using two approaches: experimental approach based on a hardware-in-the-loop testing and a simulation approach using the French regulatory calculator.

Keywords: Hardware in the loop ; hybrid heat pump ; sizing rules ; electric heat pump ; heating coverage rate

1. Introduction

The French residential sector accounts for approximately 30% of final energy consumption and nearly 25% of national CO_2 emissions, with heating alone representing about two-thirds of household energy use, primarily fuelled by natural gas and fuel oil [1]. Transitioning to sustainable energy systems is therefore a major challenge.

In line with its commitment to carbon neutrality by 2050, France has implemented initiatives such as the SNBC (Low Carbon National Strategy) and the PPE (Pluriannual Energy Program) to reduce emissions and promote renewable energy [2]. Improving energy efficiency and decarbonizing heating systems are key objectives of this transition. Residential buildings mainly rely on natural gas (41% in 2018) and electricity (37% in 2018) for space heating and Domestic Hot Water (DHW) [3], using gas boilers and electric systems. With evolving regulations, natural gas boilers are being phased out with a push towards green gases or full electrification: since 2022, gas boiler installations are limited in new dwellings under the most recent environmental building regulation RE2020. However, full electrification of space heating is challenging for the existing French electricity grid (an aging, unsuitable and undersized grid for full electrification) and can encounter architectural, technical or economical constraints.

Hybrid Heat Pumps (HHPs) combining an electric heat pump, a condensing gas boiler, and a smart control system offer a promising transitional solution, reducing CO_2 emissions while supporting grid stability. Several studies have analysed HHP performance, sizing, and control strategies. For instance, Dongellini and al. investigated the impact of HHP sizing and control strategies, but their work was purely simulation-based without experimental validation [4]. Similarly, Hangyu Liu and al. applied deep reinforcement learning control to optimize hybrid heat pump systems, yet the study remained computational [5]. Other works focused on simulations to optimize the cut-off or bivalent temperature, but not directly the heating coverage rate, as highlighted in [6], [7]. Field tests of HHPs have been conducted to assess the benefits of smart control technologies, such as in [8], but these studies often used deliberately small heat pump sizes, which were insufficient to fully heat the building, and were not intended to determine optimal sizing. Predictive control

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procedures have also been explored, but again the focus was on control performance rather than sizing optimization.

The heating coverage rate is a key performance indicator of HHPs, as it reflects the proportion of the heating demand met by the HP component under real operating conditions. The purpose of the sizing rules is to optimize the heating coverage rate—an essential factor for ensuring the expected energy savings and CO_2 emission reductions—while minimizing the initial investment cost (CAPEX) of the HHP. This subject was addressed in [9] where a methodology was proposed to optimize the electrical heat pump size with respect to necessary heating load.To ensure the reliability of these theoretical assessments, this study focuses on the experimental validation of calculated heating coverage rates for HHP. The experimental campaign will thus play a critical role in confirming the accuracy of the simulation models and in demonstrating the practical effectiveness of HHPs in delivering low-carbon heating.

Section 2 presents the HHP system along with the KPIs considered, the experimental setup based on hardware-in-the-loop (HIL) testing, and the simulation methodology. Section 3 details the simulation results, providing both an average representation of the French residential building stock using the French regulatory calculator (an hourly time-step dynamic building energy simulation engine) and results from the manufacturer's internal tool compared with the experimental results, based on the different tested configurations.

2. Methods

2.1. Hybrid Heat Pump system

This article focuses on a HHP with base-load HP and auxiliary boiler control. In this type of control, the HP operates as the primary heating source, providing the base thermal load, while the boiler supplements the heat supply when the heat pump alone cannot meet the demand, for example during cold periods, as illustrated in Figure 1. This approach ensures efficient operation of the heat pump while maintaining comfort and reliability [9].

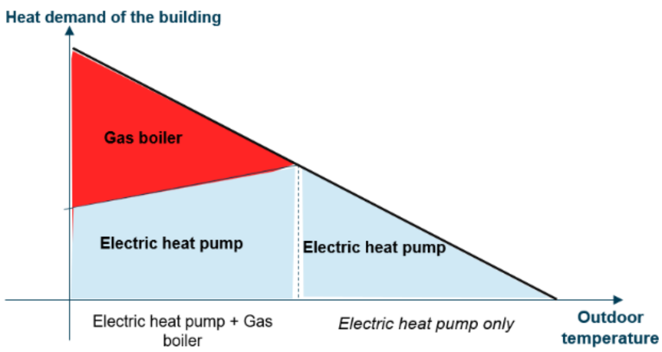

Figure 1. HHP with base-load heat pump and auxiliary boiler regulation

Hybrid heat pumps can generally be found in three main configurations:

- Dual-service (DS) heat pump + DS boiler: the heat pump covers both space heating and domestic hot water (DHW), with the boiler as backup.
- Heat pump by usage + DS boiler: the heat pump is dedicated to one service (either heating or DHW),while the boiler can supply both services or cover the other one.
- Heating-only heat pump + DS boiler: the heat pump covers space heating only, while the boiler handles DHW as well.

This study focuses on the third configuration, the heating-only HP combined with a dual-service (DS) boiler, which is widely used and allows for a clear analysis of HP sizing for space heating, while the boiler ensures DHW supply and peak demand coverage. Using the French regulatory calculation engine [10], several HHP sizing scenarios were simulated across different building typologies, ranging from well-insulated to poorly insulated buildings, and under three French climatic zones.

According to the French energy efficiency regulations, HHP systems can qualify for financial incentives such as white certificates subsidies, provided that the electric HP ensures a significant share of the building's heating demand. The regulatory framework establishes that the HP must cover at least 70 % of the annual heating needs under standard operating conditions to be considered the primary heating system.

The heating coverage rate is defined as the fraction of the total space heating demand supplied by the HP over the period considered (Eq. (1))

$$Heating\ coverage\ rate\ [\%] = \frac{Q_{HP}}{Q_{total}} \tag{1}$$

Where :
Q_{HP} is the thermal energy provided by the HP kWh/year
Q_{Total} is the total heating energy supplied to the building (HP + boiler) kWh/year

In this context, the HP capacity ratio is calculated according to Eq. (2). Its value represents the primary focus of the calculations performed to establish the product's sizing rules.

$$HP\ capacity\ ratio\ [\%] = \frac{P_{HP}(0/50°C)}{P_{heating}(Tbase)} \tag{2}$$

Where :
$P_{HP}(0/50°C)$ is the electric HP capacity at A0°C/W50 °C
$P_{heating}(Tbase)$ the building's base-load heating demand at the base temperature. The base temperature is the design outdoor temperature assigned to each geographical location. It is derived from long-term meteorological records and corresponds to a low-probability minimum temperature that may occur only a few hours per year. In metropolitan France, the current design base temperature generally ranges from –15 °C to –3 °C.

This study aims to compare these KPIs using both simulation and experimental approaches.

2.2. Buildings typologies used to validate simulations thanks to experimental tests

While numerous simulations have been conducted to estimate the heating coverage rate across various configurations [9], this study goes a step further by validating the simulation results through experimental testing. This approach strengthens the reliability of sizing rules that are essential for guiding professionals in system design.

To this end, eight configurations have been defined by combining building typologies, climatic zones and a variation of HP sizes. The HHP used correspond to commercially available units, representative of typical market capacities. The main characteristics of the tested configurations are summarized in Table 1.

Table 1. Buildings and HPs sizing

Configuration	Buildings' heat load (kW)	HP capacity ratio (Eq 2)
#1	59	52.0%
#2	76	40.4%
#3	36	85.3%
#4	46	66.7%
#5	59	26.0%
#6	76	20.2%
#7	36	42.7%
#8	46	33.4%

These combinations of buildings and HP allow to cover a large range of sizing ratios, with ranging HP capacity ratio between 20.2% and 85.3%.

2.3. The experimental approach

After performing dynamic simulations of HHPs across different building typologies, an experimental phase is conducted to validate these simulations using a semi-virtual test bench. This test bench integrates Hardware-in-the-Loop (HiL) methodology, which has emerged as a robust methodology for assessing Heating, Ventilation, and Air Conditioning (HVAC) systems under realistic operating conditions. By integrating physical components with virtual building models and environmental simulations, HiL enables real-time evaluation of control strategies and system responses to dynamic climatic and load scenarios [11], [12].

The integration of HiL with advanced commercial simulation platforms (eg. Dymola, EnergyPlus, MATLAB/Simulink, etc.) further enhances its capabilities. These platforms enable co-simulation of building models, occupant behavior, and grid interactions, allowing for comprehensive performance assessments.

To optimize the experimental testing period, the heating season is condensed into five representative days using the k-medoids clustering algorithm. This technique offers robust time series classification and reduces sensitivity to outliers [13].

HiL can therefore be considered as a step between simulation and field tests, the latter being costly. Its advantage remains in giving engineers and researchers insights to HVAC systems under near-real-world conditions through seasonal efficiency and control strategies evaluation. As energy systems become more complex, HiL testing plays a central role in the design, testing, and deployment of then newest HVAC technology.

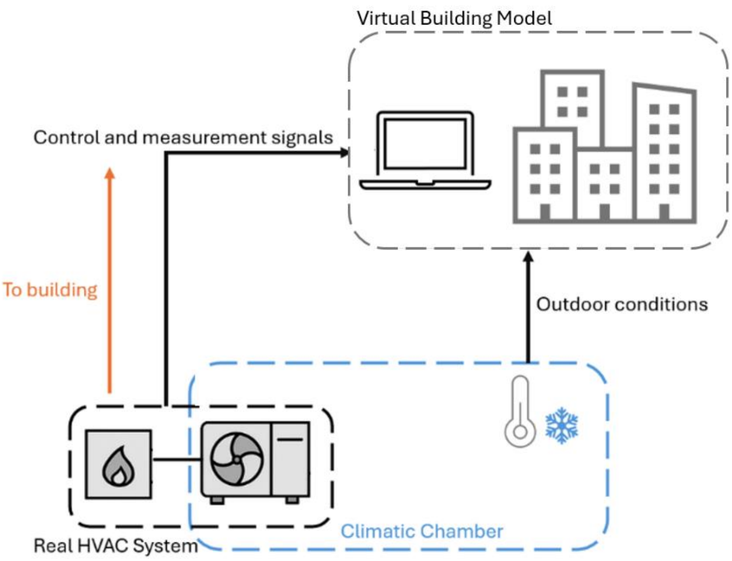

Figure 2. Operating principles of the HiL tests

In this study, a HiL framework is used to investigate the seasonal performance and operational behavior of commercially available HHPs. The emulated component of the HiL framework consists of the building envelope (cf. Figure 2). Representative multi-family dwellings located in France are considered and modeled, using Dymola software and based on Modelica buildings library developed at Berkeley [14]. The modelling assimilates each building into 3 thermal zones (top floor, ground floor and intermediary floors). The composition of the buildings is of typical French collective dwellings and are extracted from the ENERTER database [15]. The HiL setup is coupled with a climatic chamber to replicate outdoor environmental conditions, where the external units of the HHP are installed (Figure 2), where the heating season was condensed into 5 representative days. A sensitivity testing study was conducted by varying the heat pump size of the HHP with respect to the total thermal load of the buildings as shown in Table 1.

The tests are carried out on a semi-virtual laboratory bench, allowing identical test conditions to be reproduced across different systems, enabling direct comparison of the obtained results:

- The tests are focused exclusively on space heating.
- The hydraulic layout follows the recommended configuration from the manufacturer.

- The control strategy is based on the heat pump operating as the base load and the boiler as backup, with the bivalent temperature set according to the data provided by the manufacturer's tools, depending on the test conditions.

Therefore, evaluating the system performance under representative and reproducible operating conditions is possible.

2.4. The simulation approach of the building stock

The present work evaluates a sensitivity analysis on the sizing of HHP, integrating different capacities of electric heat pumps under a base-load control strategy. In this configuration, the HP provides the main heating demand, while the gas boiler acts as backup.

An initial simulation is conducted at the building stock's scale by modelling typical configurations of French residential buildings equipped with collective gas heating systems as it was done in [16]. The selected typologies are established to capture the diversity of the national building stock in terms of geometry, insulation level, and thermal properties. These reference buildings and their associated parameters are defined and validated in [15] which provides a comprehensive description of the methodology used to characterize the French building stock and to select representative cases for simulation. In this study, five representative building typologies with collective heating systems are considered: small multi-family buildings, large multi-family buildings, elongated blocks, intermediary buildings, and standard collective buildings. Each typology corresponds to a specific architectural morphology. For each one, several insulation levels are analysed, reflecting different construction periods and renovation states.

The thermal performance and energy consumption of each configuration are simulated using the French regulatory dynamic energy simulation engine (COMETh/Th-BCE), which is validated by international standards. This tool, consistent with the French EP-regulation framework, enables detailed hourly simulations of heating needs, system operation, and energy balances, accounting for climatic conditions, envelope characteristics, and heating system typology. The modelling framework and its validation procedures are fully documented in [10].

To better capture the variability of HP performance, the HHP simulations incorporate the performance and power matrices of the heat pumps, based on the EDIBATEC database [17], which compiles extensive manufacturer-declared values for various heating and DHW equipment. The mean COP at 7/35 is 4.5. For this study, HPs within the required power range were selected, and an average of the performance and power coefficients was calculated to represent typical characteristics of market-available HPs. This approach allows for a realistic simulation of HHP behaviour and enables a robust assessment of system sizing and energy performance.

Subsequently, the buildings used in experimental tests are selected from the portfolio and modelled using the internal simulation tool and the real HPs data of the manufacturer. These simulations provide an additional perspective on the simulation results obtained with Th-BCE.

In the simulations, with the HP operating as the base load and the boiler as backup, a fixed bivalent temperature is used, specific to each building typology. Similarly, for the experimental tests, the operation is also based on a fixed bivalent temperature determined according to the manufacturer's recommendations.

3. Results and discussion

The sizing of heat pumps in HHP is primarily based on calculation methods aimed at determining optimum between HP ratio and heating coverage rate. These methods are sufficiently robust to accommodate the diversity of building typologies and climatic conditions, thereby minimizing the risk of incorrect sizing, occupant discomfort, counter-references, etc. These methods make it possible to cover a wide range of sizing ratios (e.g. between 5 and 75% of the total losses) by characterizing the HP performance (SCOP, heating coverage rate, etc.) for different installed capacities. However, a purely model-based approach may introduce systematic biases due to simplifications or assumptions that fail to capture real-world variability. To mitigate these limitations, experimental data and measurements of eight configurations (ie combination of type of building, climate zone and HP sizing) serve as essential complements, enabling validation and refinement of theoretical models and ensuring greater reliability and applicability across contexts.

3.1. HiL testing results

The heating coverage rate (Eq 1) is evaluated based on experimental measurements, considering the fraction of the total heating demand supplied by the HP for the eight tested configurations presented in Table 1. The HPs are evaluated in the HiL bench under the climatic conditions representative of northern France, corresponding to the H1 climatic zone in the French building sector.These results are summarized in Figure 3.

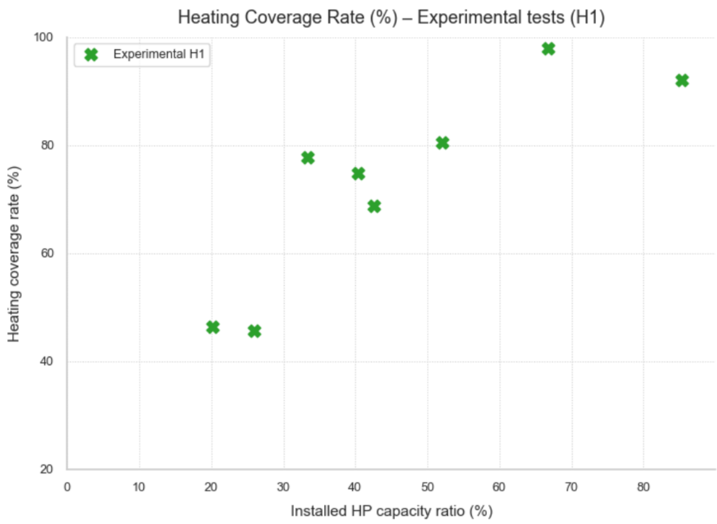

Figure 3. Heating coverage rates (%) of HHP obtained from experimental tests

The heating coverage rate logically increases with HP capacity and reaches nearly 100%. The progression of the coverage rate as a function of the HP capacity indicates that, to achieve a coverage rate of 70 %, the heat pump capacity ratio must exceed 30-35 %. These results are derived from eight configurations. The next step is to assess whether the observed HHP behaviour is consistent when extended to the full building stock.

3.2. Calculations of the French building stock and specific buildings

Prior to the comparison between measured and simulated data for the most representative building typology (small collective), a preliminary modelling phase is conducted across the entire stock of multi-family residential buildings. This analysis is based on the five most representative typologies of the French building stock, each characterized by multiple levels of thermal insulation and simulated under several climatic zones (H1-northern France, H2-center of France and H3 – southern France). The objective is to use simulations to derive the curve that characterizes the relationship between heating coverage rate and HP capacity ratio for the entire French building stock, with the aim of supporting the generalization of sizing rules.

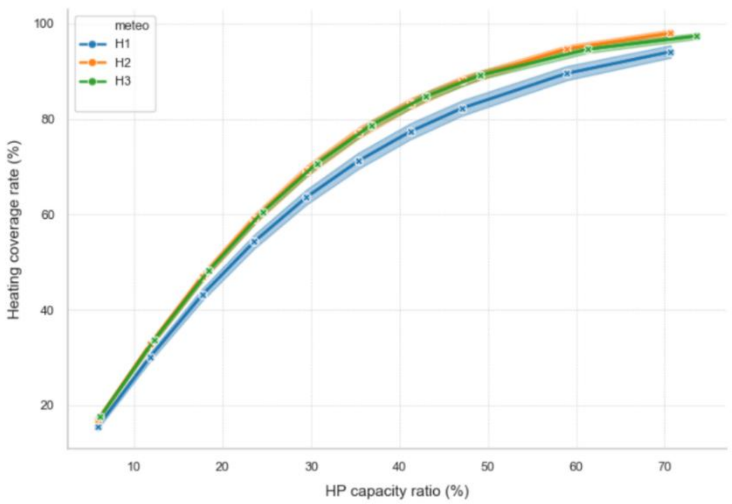

Figure 4. Heating coverage rates (%) for HHP obtained from Th-BCE simulations

The trend shown by this curve is similar to that of Figure 3. It therefore provides valuable guidance for identifying the minimal HP sizing ratio that ensures a sufficient heating coverage and, consequently, eligibility for financial support schemes (e.g., white certificates). Conversely, higher HP capacities lead to increased CAPEX and also total updated cost. The optimal sizing ratio thus results from a trade-off between costs and energy performance [9].

According to the results in Figure 4, achieving a coverage rate of 70 % requires a HP share exceeding 30 % (H2 and H3, the centre and South of France) and 35% for H1 (North and East of France). Below this threshold, the HP can still be sized, but the coverage rate falls below 70 %, making the system ineligible for certain subsidies under French regulations (typically white certificates).

3.3. Manufacturer calculation

To assess the consistency of the simulation results, a comparative study was conducted in collaboration with different manufacturers representing the French and European markets. The comparison with the manufacturer of the tested HHP during the experimental phase is presented. This targeted comparison enables an initial pre-validation of the COMETh\Th-BCE simulation model.

The study involved providing the manufacturer with two building typologies (small multi-family and large multi-family), each defined with two levels of thermal insulation, consistent with those used during the experimental phase.

Using the input data for these typologies across the three climatic zones (H1, H2, and H3), the manufacturer performed calculations with their in-house simulation tools to determine :

- the heating demand covered by the heat pump, and
- the heating coverage rate %

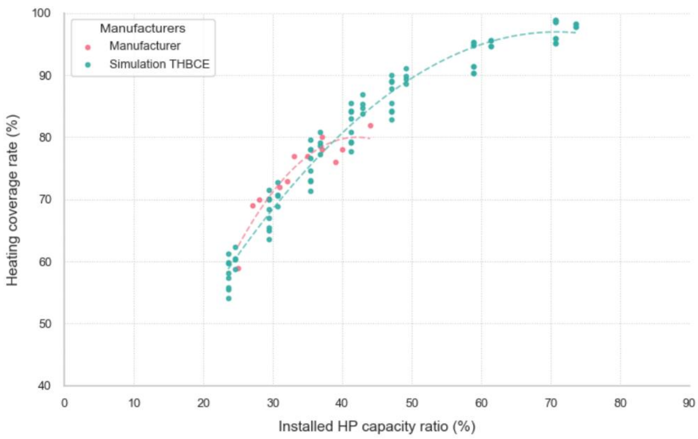

Figure 5. Heating coverage rates (%) for HHP obtained from Th-BCE simulations and manufacturers' simulation tools

Figure 5 presents the heating coverage rates (%) obtained from simulations performed from the results provided by the manufacturer simulation tools and using the COMETh\Th-BCE calculation engine.

Including this data in the study is important to validate that the simulations conducted are consistent with manufacturer's results, and that the simulated heating coverage rate appears to be largely independent of the energy simulation tool used.

3.4. Comparison measurements and calculations

Laboratory tests are not always feasible; however, when they can be performed, they provide significant added value. They offer complementary insights to simulation results, reflect the actual behaviour of systems, and help avoid potential modelling biases. This section compares the results obtained from the experimental tests, the results obtained by the manufacturer tools and all the results obtained from the COMETh\Th-BCE calculation engine, obtained from calculations at the building stock scale. Figure 6 compares the heating coverage rates from the experiments and the simulations in a single graph. Some points lie slightly above or below the simulation results, with an average deviation of 3–5 %, illustrating the overall good agreement between the two approaches. For example, for a 40% HP capacity ratio, the heating coverage rate is around 75% from the experimental testing, 76% with COMETh\Th-BCE tool and the manufacturer internal tool.

These results validate the experimental approach as well as the robustness of the HiL method, where the HHP system control intricacies influence the total performance of the system. They also highlight that the simulation tools used are valid and coherent with system behaviour under near real life conditions. They therefore could be used as a pre-selection tool when HiL testing is impossible or too expensive. The results also underline their ability to extrapolate the results for other conditions. Hence, both methods are complementary and important as they could offer a more holistic estimation of system behavior and predict performance and CO_2 emissions reduction.

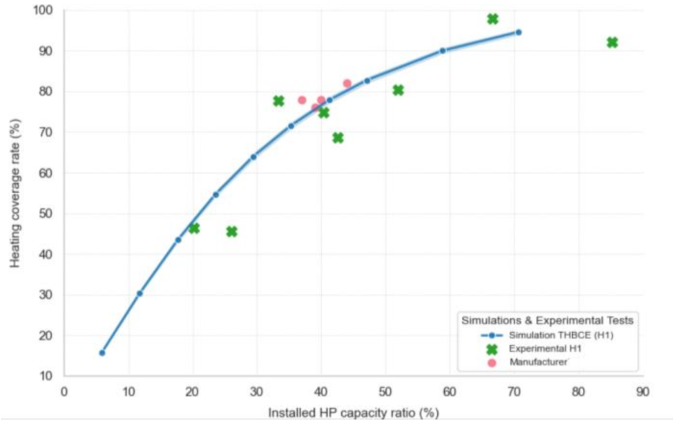

Figure 6. Heating coverage rates (%) for HHP obtained from experimental tests and simulations

4. Conclusions

The heating coverage rate of the electric HP within a HHP system represents the share of total heating demand supplied by the HP. In an HHP configuration where the HP operates as the base load and the gas boiler provides backup, the HP delivers the maximum possible share of heating demand, while the boiler compensates for the remainder. Using the regulatory Th-BCE calculation engine, a sensitivity analysis is conducted for various HP shares. Based on the heating demands of the studied building typologies, this approach allows the determination of the heating coverage rate for each configuration. These results are compared with manufacturer's simulations based on detailed performance maps of their HHP systems. In contrast, the Th-BCE engine relies on average performance data from the EDIBATEC database. The comparison demonstrates that Th-BCE simulations are representative of overall system behaviour, with results closely aligned with manufacturer data. A few HHP models achieve slightly higher coverage rates (above 70 %) due to advanced design and improved HP performance. Experimental results further validate these findings, confirming that a heating coverage rate of 70 % is reached with an HP share between 30 % and 35 %, depending on the case. Finally, the use of the Th-BCE engine and the resulting simulations offers a robust framework for determining the optimal sizing of HHP systems. Setting a 70 % coverage target enables identification of the HP size required to meet white certificates criteria. This methodological foundation can also be extended to future studies focusing on techno-economic optimization and carbon abatement cost analysis.

References :

[1] Ministère Chargé De l'Energie, "Stratégie française pour l'énergie et le climat." Nov. 2024.

[2] Ministère de la Transition écologique, de l'Énergie, du Climat et de la Prévention des risques, "Planifier une France décarbonée : Mise en concertation de la PPE et de la SNBC." Accessed: Oct. 28, 2025. [Online]. Available: https://www.ecologie.gouv.fr/sites/default/files/documents/202411_DP_SNBC_PPE_0.pdf

[3] Agence Internationale de l'Énergie (AIE), "Energy Policies of IEA Countries: France 2021 Review," Rapport d'examen des politiques énergétiques, Nov. 2021. [Online]. Available: https://iea.blob.core.windows.net/assets/7b3b4b9d-6db3-4dcf-a0a5-a9993d7dd1d6/France2021.pdf

[4] M. Dongellini, C. Naldi, and G. L. Morini, "Influence of sizing strategy and control rules on the energy saving potential of heat pump hybrid systems in a residential building," *Energy Conversion and*

Management, vol. 235, no. 114022.
[5] Hangyu Liu *et al.*, “Application analysis of hybrid heat pump heating systems optimized with deep reinforcement learning control,” *J. Build. Eng.*, vol. 113, 2025, doi: https://doi.org/10.1016/j.jobe.2025.114024.
[6] G. Bagarella, R. Lazzari, and M. Noro, “Annual simulation, energy and economic analysis of hybrid heat pump systems for residential building,” *Appl. Therm. Eng.*, vol. 99, pp. 485–494, Apr. 2016, doi: https://doi.org/10.1016/j.applthermaleng.2016.01.089.
[7] Marco Beccali, Marina Bonomolo, Francesca Martorana, Pietro Catrini, and Alessandro Buscemi, “Electrical hybrid heat pumps assisted by natural gas boilers: a review,” *Appl. Energy*, vol. 322, p. 15 september 2022, doi: https://doi.org/10.1016/j.apenergy.2022.119466.
[8] M. Sun, P. Djapic, M. Aunedi, D. Pudjianto, and G. Strbac, “Benefits of smart control of hybrid heat pumps: An analysis of field trial data,” *August 2019*, vol. 247, pp. 525–536, Jan. 2019.
[9] D. Da Silva, G. Abou Rached, and D. Dupuis, “Hybrid Heat pumps in Collective Buildings, a good agreement for Energy transition,” presented at the 2023 Building Simulation Conference, Sept. 2023. doi: 10.26868/25222708.2023.1604.
[10] D. Da Silva, J.-M. Alessandrini, J.-B. Videau, C. Pelé, and J.-R. Millet, “Evaluation et perspectives du modèle thermique de COMETh, le coeur de calcul de la réglementation thermique des bâtiments neufs,” in *IBPSA France*, Marne-la-vallée, 2016.
[11] L. F. Cabeza, D. Verez, and M. Teixidó, “Hardware-in-the-Loop Techniques for Complex Systems Analysis: Bibliometric Analysis of Available Literature,” *Appl. Sci.*, vol. 13, no. 14, p. 8108, Jan. 2023, doi: 10.3390/app13148108.
[12] W. El-Baz, L. Mayerhofer, P. Tzscheutschler, and U. Wagner, “Hardware in the Loop Real-Time Simulation for Heating Systems: Model Validation and Dynamics Analysis,” *Energies*, vol. 11, no. 11, p. 3159, Nov. 2018, doi: 10.3390/en11113159.
[13] X. Jin and J. Han, “K-Medoids Clustering,” in *Encyclopedia of Machine Learning*, Springer, Boston, MA, 2011, pp. 564–565. doi: 10.1007/978-0-387-30164-8_426.
[14] M. Wetter, W. Zuo, T. S. Nouidui, and X. Pang, “Modelica Buildings library,” *J. Build. Perform. Simul.*, vol. 7, no. 4, pp. 253–270, 2014, doi: 10.1080/19401493.2013.765506.
[15] Energies Demain, “ENERTER bâti.” 2022. Accessed: Jan. 27, 2025. [Online]. Available: https://energies-demain.com/enerter-bati/
[16] J.-B. Videau, N. El Harakat, and G. Abou Rached, “Hybrid Heat Pumps, the answer for the future electric grids?,” *Build. Simul.*, 2025, doi: https://doi.org/10.26868/25222708.2025.1265.
[17] EDIBATEC, “EDIBATEC – Base de données produits pour la simulation thermique et le dimensionnement des systèmes de chauffage.” 1993. Accessed: Oct. 28, 2025. [Online]. Available: https://www.edibatec.org/consult/fabricant.php