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# Techno-economical optimization sizing study for hybrid heat pumps in collective dwellings

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**Abstract**

Hybrid heat pumps (HHPs) are heating generators that combine a gas condensing boiler with a heat pump and smart control system to optimize energy efficiency and reduce operational costs by switching between two sources of energy based on demand and external conditions. This work focuses on comparing two sizes of HHPs, balancing technical performance and economic feasibility. The different HHPs sizes were experimentally tested in a hardware-in-the-loop approach for a single use case– a collective dwelling in the climatic region of Strasbourg. The total cost over a 20-year lifespan is computed. It was found that the 40% HHP offers an optimal configuration and a good balance between overall costs and long-term savings for an electricity to gas price ratio under 2.6, thanks to the higher heat cover ratio and better efficiency. The study also highlights that HHPs are a viable economical and energy efficient alternative.

*Keywords:* Hardware in the loop; k-medoids; hybrid heat pump; seasonal efficiency; sizing rules; electric heat pump; advocacy;

## 1. Introduction

The need for reliable and efficient heating solutions is increasingly pressing, particularly in cold-climate regions such as France, where winter heating demand represents a significant share of household energy consumption [1]. The residential sector accounts for more than 40% of total final energy use in Europe, with space heating alone representing the largest end-use [2]. Within this sector, collective dwellings constitute a substantial share of the building stock, and their aggregated energy demand makes them a critical focus for decarbonization strategies. Improving heating efficiency in such buildings is therefore central to meeting both energy security and climate objectives. Without significant improvements in energy performance, especially through renovation and system replacement, the targets set by the European Green Deal and the Paris Agreement will remain out of reach. However, the economic challenges associated with building renovation are considerable. High upfront costs, long payback periods, and limited access to financing mechanisms are among the most significant barriers. Many property owners, especially in vulnerable districts and low-income households, lack the financial capacity to invest in retrofitting. Traditional gas boilers, while widely deployed and more financially accessible, face limitations in terms of efficiency and environmental impact. Conversely, electric heat pumps (HP) offer energy savings and emissions reductions but are often constrained by high upfront costs, variable performance in cold climates, and potential strain on the electrical grid. To overcome these challenges, innovative financing models and policy instruments are being explored as well as new systems are emerging.

In this context, hybrid heat pumps (HHPs) – which combine a gas condensing boiler with an electric heat pump and a smart control system – as a new system or as an add-on – have attracted growing attention as a rising solution. By dynamically switching between electricity and gas depending on outdoor conditions and load requirements, HHPs can achieve higher seasonal efficiency while keeping operational costs under control [3].

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Yet, the effectiveness of these systems depends strongly on their sizing: undersized systems may fail to reduce significantly the carbon footprint and dependency on fossil fuel energy, while oversized HHPs increase significantly capital expenditure.

This study addresses the techno-economic optimization of HHP sizing for collective dwellings. Using a hardware-in-the-loop (HiL) experimental framework, two different HHP sizes were assessed for a representative building located in the Strasbourg region of France. Both technical performance and economic feasibility are analyzed to identify the optimal balance between efficiency and cost.

## 2. Methodology and assumptions

To optimize the HHP sizing in collective dwellings, based on different key parameters, a hardware-in-the-loop (HiL) test was conducted to evaluate the response of the system in near world conditions.

In fact, as buildings and systems become increasingly complex physical systems, the need for robust, real-world validation of control strategies have become essential. HiL simulation has emerged as a powerful methodology to reduce the gap between purely virtual models and full-scale field setups. By integrating real hardware components—such as equipment—into a simulated environment that mimics the dynamic behavior of a building, HiL tests equipment under realistic conditions without the costs associated with full deployment. It is used as an intermediate step of testing, more holistic than simple laboratory testing and cheaper than field-testing. HiL is particularly valuable for evaluating Heating, Ventilation, and Air Conditioning (HVAC) control strategies. Recent studies have demonstrated the versatility of HiL platforms in smart building applications. For example, in [4] a heat pump model using a HiL testbed was validated, showing that real-time simulation can significantly improve the accuracy of dynamic system analysis and control tuning.

In this work, the building block is emulated, while the HHP is attached to the test bench to study in more detail its response to the variation of the load. The building envelope is modelled based on the Modelica buildings library developed at Berkeley [5]. The building is divided into three thermal zones: the first floor, the top floor and the intermediate floors. The building's surface area and walls' thermal resistances correspond to those of a typical small collective dwelling and extracted from the ENERTER database [6]. The building is composed of 13 apartments, each comprising 3 rooms with a 63.7m$^2$ surface area. The building's thermal characteristics are detailed in the table below:

Table 1 . U-values for the building envelopes.

| Component | U-value (W/m².K) |
|---|---|
| Walls | 1.84 |
| Flooring | 2 |
| Ceiling | 0.22 |
| Windows | 3 |

The emulated building has a total heating load of 76 kW at -15°C, the base temperature in the Strasbourg region of France [7].

To speed up the evaluation of the seasonal efficiency of the product, the heating season is condensed into 5 representative days by using the k-medoid clustering method: it 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 (Figure 1) [8].

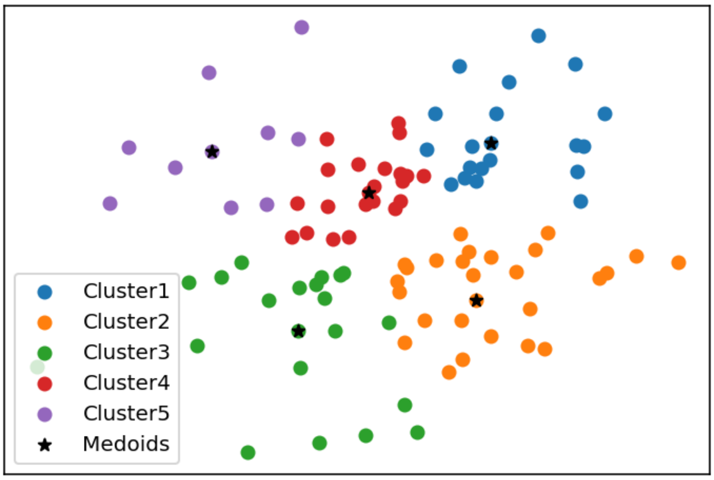


Figure 1. Illustration of the k-medoids method.

The obtained reduced weather sequence of the Strasbourg region is shown in Figure 2:

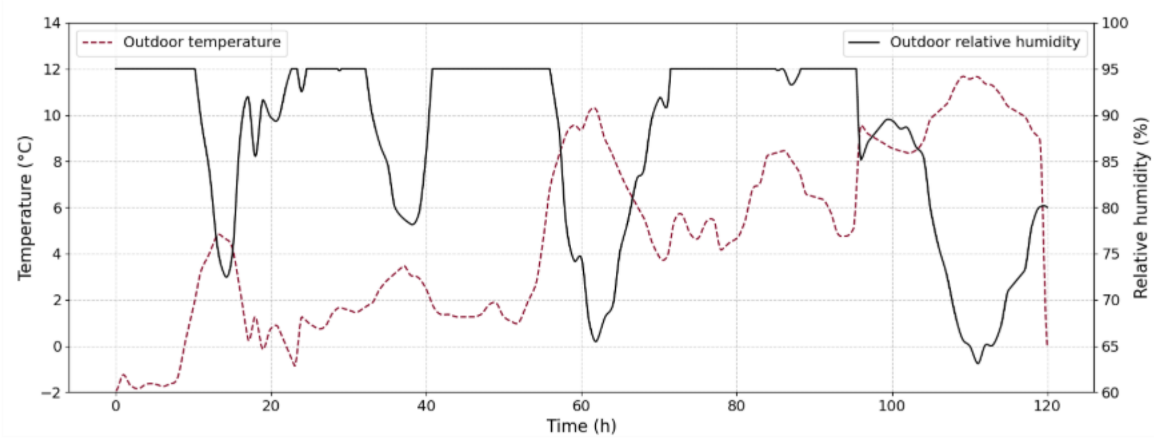


Figure 2. Temperature and relative humidity sequences for the climate region of Strasbourg.

The installation replicates the actual system and respects the manufacturer's guidelines and recommendations, as shown in Figure 3.

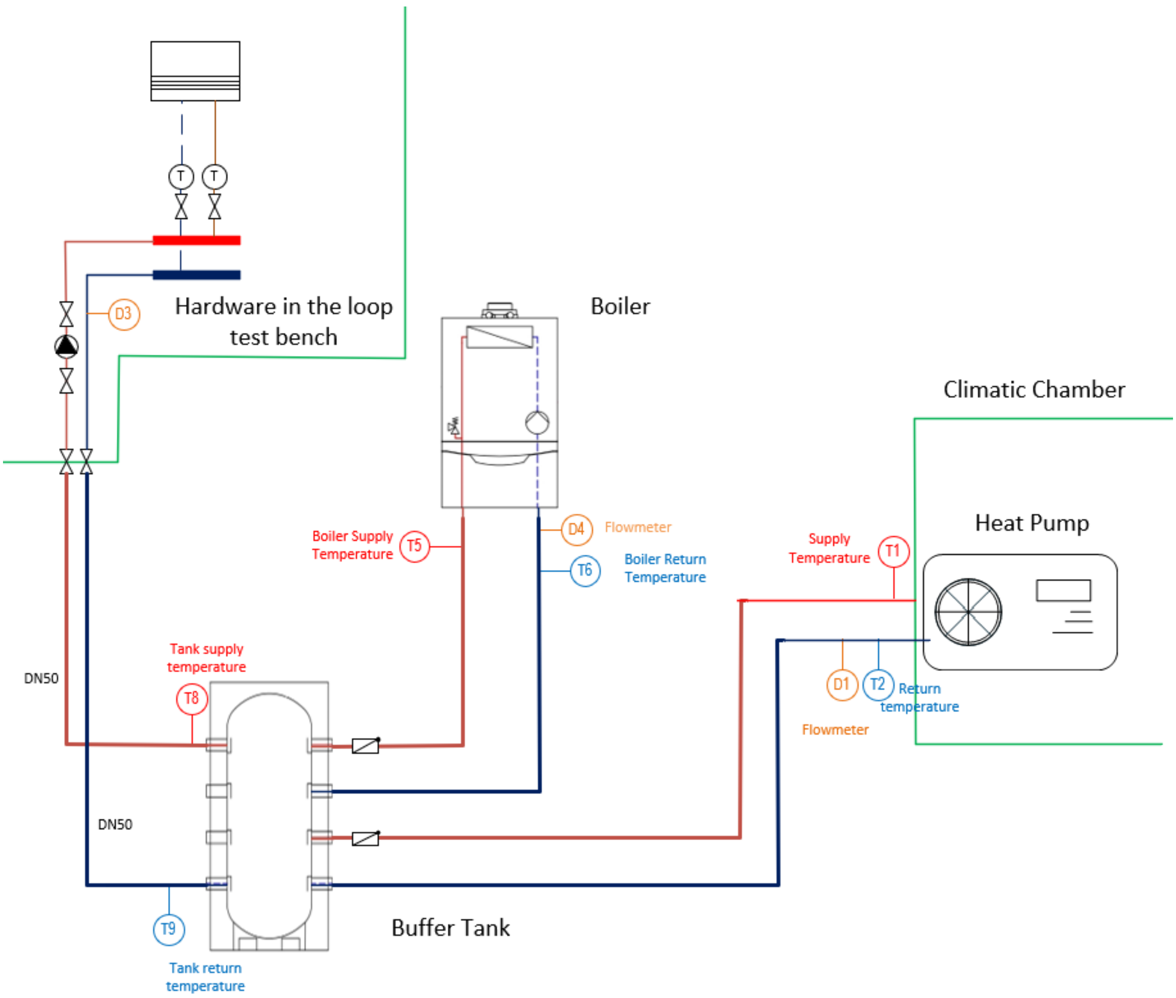


Figure 3. Test bench hydraulic installation.

To identify the most cost-effective HHP sizes for the chosen building in the climate region of Strasbourg, two commercially available HHPs, using R290 as a working fluid, are tested.

The first HHP is selected to maximize the heat cover ratio, defined as the ratio of the supplied thermal energy by the electrical component of the HHP with respect to the total supplied energy. Its size was found to be around 40% of the base load at operating temperatures of 0°C/50°C, and this configuration is referred to as **Test A**. **Test B** consists of downsizing the electrical HP to reduce initial investment costs. The same gas boiler and control system are used for both configurations.

The tested installation follows the hydraulic scheme of the manufacturer (Figure 3) and auxiliary equipment is similar in both cases. The same control parameters are put for both installations: Internal setpoint temperature of 19°C and same heating curve (70°C supply temperature at the base temperature). The same temperature and humidity sequence is used for both configurations (Figure 2) and the building envelope is kept intact (Table 1).

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. The hybrid heat pump follows a heating curve, chosen adequately to the building. The manufacturer also provides essential sensors installed inside the buffer tank and at the supply temperature and connected to the smart controller to ensure a correct behavior of the hybrid system.

The total consumed energies for both tests are computed and compared. Operational expenditures are computed based on the consumed energy and data are gathered in Table 2.

Figure 4 summarizes the testing methodology algorithm.

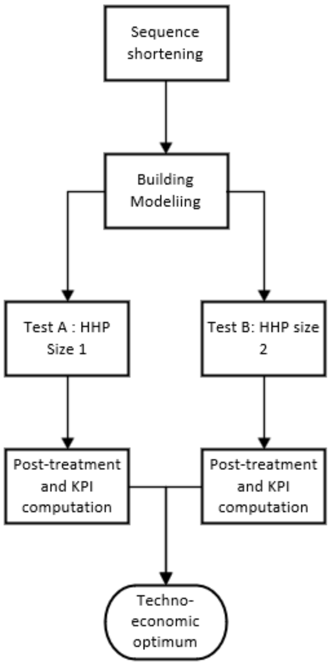


Figure 4. Testing methodology algorithm.

## 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)).

$$SCOP_{C1} = \frac{\sum W_i \int \dot{m}_1 C_p \Delta T_{1\text{-}2} + \dot{m}_4 C_p \Delta T_{5\text{-}6}]\, dt}{\sum W_i \int (P_{elec\ \text{-}HP} + P_{elec\ \text{-}boiler}).PEF + P_{gas\ \text{-}boiler}\, dt} \quad (1)$$

Where
$W_i$ is the weight of each day of the 5-day sequence
$\dot{m}$ is the mass flow rate (kg/s)
$\Delta T$ 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 [12].

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

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

## 4. Results and discussion

Data gathered was computed with respect to instrumentation added in the hydraulic installation (Figure 3), where temperature probes were installed at the inlet and outlet of each component of the HHP. Flowmeters were also added to measure the water flow inside the installation. Measurements were recorded at a 1-second time step.

All parameters presented in Table 2 were computed using weighted sums: each representative day was assigned a weight equal to the size of its cluster (the larger the cluster the greater weight this day had). All efficiencies were computed in primary energy (PE) and high heating value (HHV). The HHV of the natural gas consumed was measured at the inlet of the testing facility. The initial investment cost takes into account the price of the HHP (electrical heat pump and boiler), auxiliary systems (control modules, outdoor temperature sensors and buffer tank), and reflects typical values from the French market.

Table 2. Computed data for both configurations.

| **Parameter** | **Test A** | **Test B** |
|---|---|---|
| Electric HP Size (at 0°/50° with respect to the base load) | 40% | 21% |
| Cover Ratio | 75% | 46.4% |
| HHP SCOP (HHV, PE*) | 1.2 | 1.11 |
| Boiler supplied energy (MWh) | 22.2 | 49.2 |
| Boiler efficiency (HHV) | 94.5% | 96% |
| Consumed gas (MWh) | 23.3 | 50.6 |
| HP supplied energy (MWh) | 66.2 | 42.6 |
| HP SCOP (Final energy) | 3.1 | 3.1 |
| Consumed electricity (MWh) | 21.3 | 13.7 |
| Initial investment cost (k€) | 35 | 21.4 |

**Primary to final energy factor in France is 2.3 [9]*

Table 2 shows that for **Test A**, the cover ratio is around 75%, higher than **Test B** where it is around 46%. This is an expected result, especially since the installed HP's power is larger in **Test A** (nearly double). This is translated in the seasonal efficiency of the HHP, where in **Test A** it amounts to 1.2 [HHV; PE], higher than **Test B** (1.11 [HHV;PE]). In both tests, the same energy is supplied to the building (around 90 MWh). The consumed energies (gas and electricity) were computed for both tests, considering the measured efficiency of each system. These values are important to estimate the operational costs of both systems.
The case study, as already detailed, is of Strasbourg France. Hence, the energy prices used in this study were for the second semester of 2024 in France, being 9.39 c€ per kWh for gas [10] and 22.23 c€ per kWh for electricity [11]. Considering the French energy prices for S2 of 2024, the energy price ratio is about 2.37. When comparing the two configurations, the data shows that **test A** configuration is more interesting over the lifespan of the installation (20 years). In fact, to better compare the systems on the long term, a sensitivity study over the operational expenditure (OPEX) was conducted, by varying electricity to gas prices, with a fixed initial gas price, equal to 9.39c€ per kWh, over a total 20-year lifespan, without integrating maintenance costs, subscription costs nor inflation of energy prices. Total price of the installation, including capital investment and operational cost over 20 years, is presented in Figure 5.
Figure 5 shows that under a price ratio of around 2.6, it is more interesting economically to install an electric heat pump of 40% (of the total load), over the installation lifespan – similar to **Test A**. It shows, that although the initial capital cost is more important (Table 2), the higher cover ratio makes it more profitable on the long term.

Therefore, as long as the electricity-to-gas price ratio is below 2.6 in the French case, it is more cost-effective to reproduce the same sizing rules for **Test A**, and by consequence those of [12] where a technical-economic optimum was found for a 35% share of the electric heat pump with respect to the total load. It should be noted that the outcomes of this analysis are highly dependent on the initial fixed gas price.

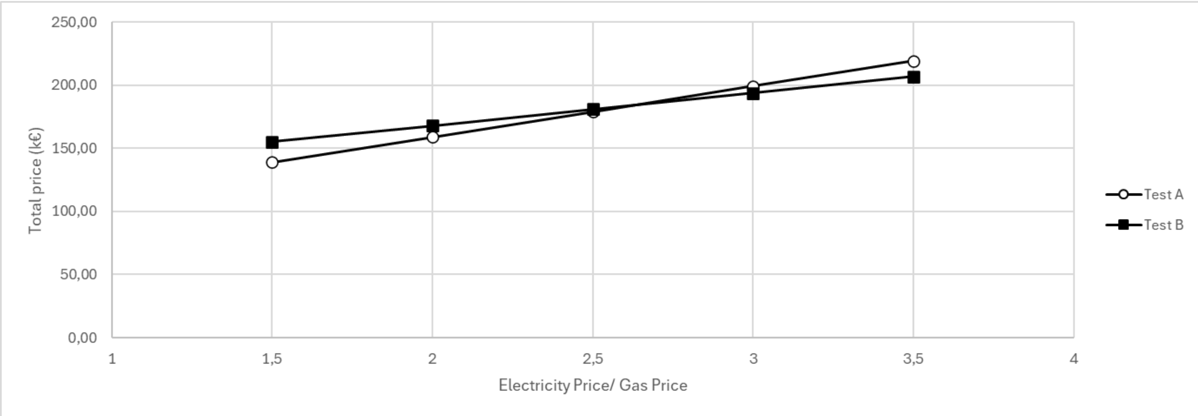


Figure 5.Variation of total installation price for both configurations with respect to energy price ratio.

This approach can of course be expanded to other regions of Europe. A new weather sequence should be generated in order to compute the energy performance of the HHP and the energy consumption (gas and electricity). Then, the total cost can be computed based on the mean prices of energy in this specific region. If we consider that the mean profile of the European weather is similar to the Strasbourg region, and the average gas and electricity prices (for household consumers in the European Union, calculated as a weighted average using 2023 consumption data and prices from the second half of 2024) were respectively €0.1233 per kWh [10] and €0.2872 per kWh [11] giving a ratio of 2.33. If the same approach is applied as precedingly, then for an electricity-to-gas price ratio under 2.86, **Test A** configuration remains interesting (Figure 6). The findings reinforce the works [12] where 35% share of electric heat pumps was found as optimum.

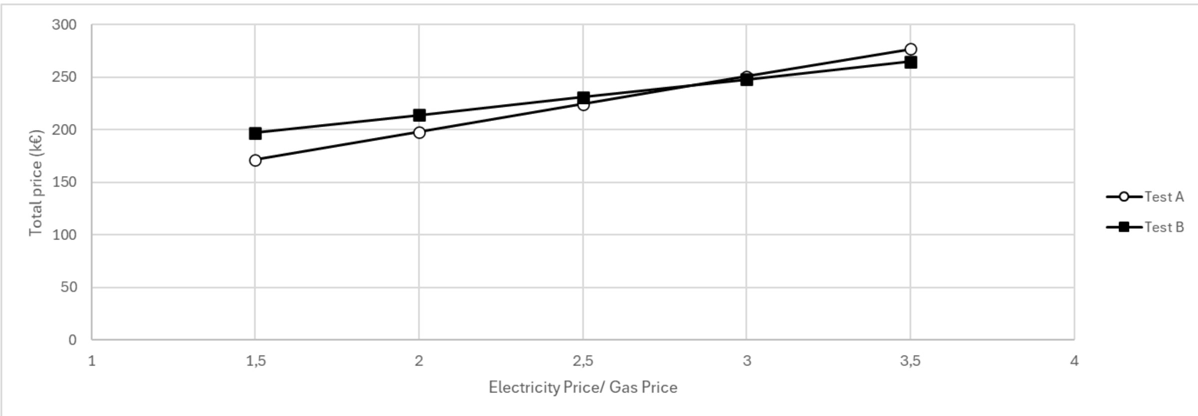


Figure 6: Variation of total installation price for both configurations with respect to energy price ratio, Europe edition

## 5. Conclusion

This study investigates the techno-economic optimization of hybrid heat pumps (HHP) sizing for collective dwellings in the Strasbourg climate region. Using an HiL experimental framework, two HHP configurations were tested (**Test A** with a HP covering 40% of the total load and **Test B** with a smaller HP) and compared in terms of technical performance and economic feasibility.

Results have shown that the system with the larger HP capacity (**Test A**) achieved a higher heat cover ratio (75% vs. 46%), and greater seasonal efficiency (1.2 vs. 1.11) compared to **Test B**. Despite its higher initial cost, **Test A** proved more cost effective over the system's lifetime: for an electricity-to-gas price ratio below 2.6 in the French context, **Test A** remained the most economically favourable configuration. This analysis highlights thereby that appropriately sized HHPs can effectively balance energy efficiency and economic performance.

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