Multi-criteria analysis of different heat pump solutions using natural refrigerant propane for existing multi-family buildings

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Abstract. Heat pumps are a proven solution for the decarbonization of the heat supply, both for space heating and domestic hot water, in individual houses. However, the implementation of heat pump systems in multi-family buildings remains marginal. The main challenges include the lowering system temperatures on the supply side (space heating and domestic hot water) and difficulties in accessing suitable heat sources in densely populated urban areas. This study presents a comparative and multi-criteria analysis of the potentials and constraints of various heat pump solutions using the natural, low Global Warming Potential refrigerant propane (R-290). It evaluates the technical feasibility and user-related aspects such as acoustics and appearance of different heat pump systems implemented in various types of existing multi-family buildings based on real case studies in Germany. After characterizing available heat sources and building demands, the energy performance of the heat pumps systems is examined through simulation. Further aspects such as the investment costs, space requirement and safety requirements due to R-290 flammability are evaluated bases on literature data and expert opinion. The findings highlight the potential of propane-based heat pumps to provide a sustainable and efficient alternative to conventional heating systems but also the complexity of finding solutions under the boundaries of existing buildings. The multi-criteria approach ensures a comprehensive assessment, offering valuable insights for policymakers, engineers, and stakeholders aiming to enhance the sustainability of heat supply in existing multi-family buildings.

Keywords: propane heat pumps, existing multi-family building, space requirement, acoustic emission, energy performance

1 INTRODUCTION

Heat pumps (HPs) are expected to play a key role to the decarbonization of the heat supply in residential buildings. In recent years, HPs have emerged as the preferred heating technology in new individual houses and are increasingly being adopted in existing individual houses. However, existing multi-family buildings (MFBs) present challenges for this technology. High flow temperatures, limited installation space, and the limited availability of ambient heat sources in densely populated areas are among the constraints that must be addressed. The *LCR290* project aims to develop technical solutions that meet these challenges and to transfer them into standardized system solutions to facilitate accelerated installation [1].

This study evaluates potential configurations of HP systems from different perspectives. The analysis is based on two case study sites with existing MFB owned by the project's advisory board. Two development pathways are being explored: first, HP solutions to replace centralized fossil fuel boilers in buildings and second, concepts designed to replace decentralized (wall-hung) gas boilers in individual apartments.

2 METHODS

2.1 Description of the case study sites

Two case study sites are briefly described in this section: one featuring centralized heat supply system and the other employing decentralized heat supply system. Suitable HP solutions are evaluated for each application. The building geometry is also considered, particularly in the design of the source energy network for decentralized HPs.

Case study site with centralized heat supply system. This site is in Potsdam, northeast Germany. The MFB is a Wilhelminian-style building constructed in 1915, situated in a densely populated urban area characterized by three to four-story perimeter block buildings. This corner MFB consists of 18 apartments, with a total heated floor area of 1,074 m^2. Additionally, two small commercial units on the first floor are intended for conversion into apartments. The mansard serves as a fully habitable floor. The existing heat supply system of the MFB includes a centralized gas boiler located in the basement [2]. The small building plot, measuring 376 m^2, poses challenges for utilizing geothermal energy as a heat source and for installing HPs outside the building. Notably, the MFB has not undergone any building envelope renovation measures. The simulated annual heat demand is approximately 136 MWh, with a maximum heating load of around 60 kW. The occupancy is assumed to be 27 people, with a daily hot water demand of 1.5 kWh [3]. The domestic hot water (DHW) circulation losses are estimated at 12.9 kWh/(m^2a) [4], evenly distributed throughout the year and contribute to space heating (SH) during the heating period.

Case study site with decentralized heat supply system. This site is in Schönebeck, about 100 km southwest of Potsdam. The MFH was constructed in 1938 and contains 23 apartments, distributed across three separately accessible, three-story building sections.

Most of the apartments are small two-room units with an average heated floor area of 42 m^2, while a few four-room units have a heated floor area of around 80 m^2. The hip roof is used for storage sheds, while the basement provides additional storage and laundry rooms. SH and DHW are supplied by decentralized gas boilers installed in the kitchens. The building envelope has not been renovated for energy efficiency. According to the energy performance certificate, the energy consumption is 135 kWh/(m^{2}a) (efficiency class E), with a standard heating load of 77 kW for the entire building. This study focuses on one of the smaller apartments, which has a heating load of 3.3 kW under standard conditions; its floor plan is shown in Fig. 1. Both the kitchen, measuring 8 m^2, and the bathroom, measuring 4 m^2, are compact, with no additional storage space available. This floor plan presents challenges for accommodating a HP with a thermal energy storage (TES). Regarding the DHW demand, an occupancy of two persons is assumed.

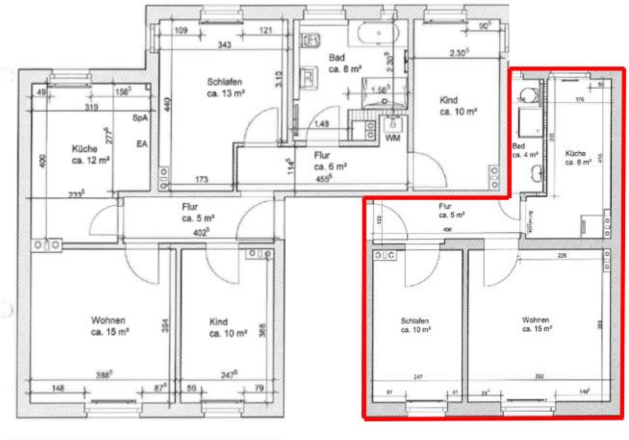

Fig. 1. Floor plan of the apartment assessed for decentralized heat pump systems

2.2 System variants with propane heat pumps

All system variants examined are listed below, with a focus solely on monoenergetic solutions.

Centralized heat pump systems. Table 1 summarizes the examined system variants with centralized propane HPs. Systems C1 to C4 include centralized brine-water heat pumps (BWHPs) installed within the building, while systems C1 to C3 utilize borehole heat exchangers (BHEs) as the heat source, and system C4 utilizes a centralized air-cooled heat exchanger (ACHE) installed outside the building. The ACHE in system C4 preheat the brine supplied to the BWHPs. This split configuration of the ACHE and the BWHP allows for the omission of R-290-related safety requirement for the outdoor monoblock units. In contrast, systems C5 to C7 include centralized monoblock air-water heat pumps (AWHP) installed outside the building, which need to consider the external safety restrictions for outdoor units with R-290 as refrigerant. Systems C1 and C5 utilize electric instantaneous water heaters (EIWHs) in the apartments for DHW supply, eliminating corresponding DHW circulation heat losses. In systems C3 and C7, DHW is supplied by decentralized heat interface units (HIU) in the apartments. In Germany, systems with decentralized HIU count as “small system” according to the regulation DVGW sheet 551, allowing for a reduced water temperature of 50 °C to 55 °C in the DHW distribution network and TES [5]. Electric heaters (EH) serve as backup for all system systems.

Table 1. System variants examined for the centralized heat supply.

Variants	**Centralized components for**			**Decentralized components for DHW**
	SH and DHW	**SH**	**DHW**	
C1	-	BHE + BWHP + TES + EH	-	EIWH
C2	BHE + BWHP	TES + EH	TES + EH + HIU	-
C3	BHE + BWHP	TES + EH	TES + EH	HIU
C4	ACHE + BWHP	TES + EH	TES + EH+ HIU	-
C5	-	AWHP + TES + EH	-	EIWH
C6	AWHP	TES + EH	TES + EH+ HIU	-
C7	AWHP	TES + EH	TES + EH	HIU

Table 2. System variants examined for the decentralized heat supply.

Variants	**Heat sources**	**Decentralized components for**		
		SH and DHW	**SH**	**DHW**
D1	Centralized BHE + LTDN	-	BWHP + EH	EIWH
D2	Centralized ACHE + LTDN	-	BWHP + EH	EIWH
D3	Centralized BHE + LTDN	BWHP	EH	TES (60 l) + EH
D4	Centralized ACHE + LTDN	BWHP	EH	TES (60 l) + EH
D5	Centralized BHE + LTDN	BWHP	EH	TES (120 l) + EH
D6	Centralized ACHE + LTDN	BWHP	EH	TES (120 l) + EH
D7	Decentralized ACHE	BWHP	EH	TES (60 l) + EH
D8	Decentralized ACHE	BWHP	EH	TES (120 l) + EH
D9	-	AWHP	EH	TES (60 l) + EH
D10	-	AWHP	EH	TES (120 l) + EH

Decentralized heat pump systems. Table 2 provides an overview of the propane HP solutions investigated for decentralized heat supply. Systems D1 to D8 include decentralized BWHPs installed in the apartments. In systems D1 to D6, a low-temperature heat distribution network (LTDN) installed on the façade supplies low-temperature heat to the decentralized BWHPs in the apartments. The LTDN is preheated by centralized BHEs in systems D1, D3 and D5 and by centralized ACHEs in systems D2, D4 and D6. In systems D7 and D8, each apartment is equipped with a decentralized ACHE installed outside the apartments. This split configuration allows these outdoor ACHEs free from external R-290-related safety restrictions. The BWHPs installed within the building are designed as an intrinsically safe appliance with a limited R-290 charge of less than 152 g. Systems D9 and D10 include decentralized monoblock AWHPs installed outside the building. The different systems for DHW supply arise from the limited space available in the apartments (see Fig. 1 and Fig. 2). In contrast, EIWH can generally be accommodated without space issues. TES tanks of up to 60 l can be installed within the dimensions of gas boilers, while 120 liters can fit into white appliances.

2.3 Evaluation criteria

The evaluation criteria of propane HP solutions for existing MFB considered in this study is detailed in this section. The results are standardized on a numerical rating scale from 1 (worst) to 5 (best) for comparative purposes.

Energy performance. The seasonal performance factor (SPF) of the BWHP and AWHP systems was calculated using the tool *HEBAP (Heating Energy Balancing Program)* developed at Fraunhofer ISE [6]. Load profiles for SH and DHW tapping are input as time series data. The HPs are modeled using characteristic maps of the three prototypes developed within the project, which were simulated using the simulation tool *IMST-ART© (Advanced Refrigeration Technologies)* [7]. The inlet and outlet water temperatures of the radiators are assumed to be 55 °C and 45 °C at the design point, which can be achieved through partial radiator replacement. Unless otherwise specified for individual system variants, the components are dimensioned in accordance with VDI 4645 and for a bivalence point of -5 °C [3].

Indoor space requirement. For centralized heat supply systems, the space requirement is defined as the sum of the indoor installation area for the TES tanks and HPs. The size of components that can be installed in existing buildings is limited by corridor widths, door dimensions, and ceiling heights; thus, the maximum volume of a single TES tank is limited to 800 l. Larger volumes must be divided into multiple units. Accounting for insulation and hydraulic connections, the installation area for a single TES tank is assumed to be 1 m². The installation area for the HPs is derived from the prototypes developed in the project, which require approximately 0.5 m² for a rated output of 30 kW heating power. However, to ensure accessibility, a required area of 1 m² for a single HP is assumed. Up to two HPs can be arranged vertically.

For decentralized HP systems, the total construction volume of the HPs and the TES tanks is critical due to the limited available space in the apartments. Fig. 2 illustrates the four product design variants considered in this study. The starting point is the installation volume of 118 l for the existing gas boilers (typically around 450 mm (W) x 350 mm (D) x 750 mm (H)). Product design 1 is notable either for HP systems without TES, which do not require any additional installation space compared to the gas boilers (D1 and D2) or for monoblock AWHPs located outside the apartment with 60-liter TES tank (D9). For product design 2, the installation volume of the existing gas boiler is used for a TES tank of up to 60 l, while the HP is implemented in a small auxiliary device of 68 l (D3, D4 and D7).

Design 3 includes a 120-liter TES tank, which can be accommodated within the dimensions of a white appliance, freeing up the volume of the gas boiler, while the HP is implemented in a small auxiliary device of 68 l. In product design 4, the HPs are positioned in place of the existing gas boiler, and the TES tank is designed as in product design 3. Design 3 and 4 are possible for system D5, D6 and D8.

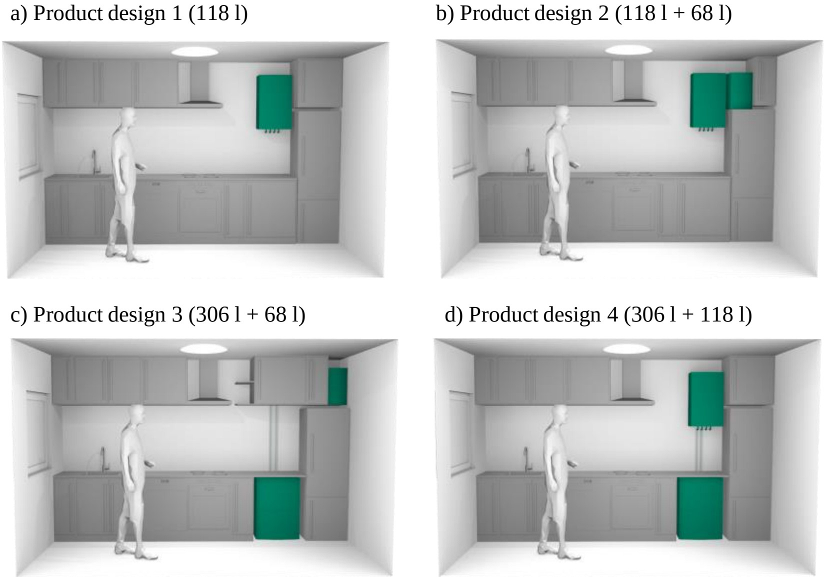

Fig. 2. Visualization of four product design variants for the decentralized heat pump solutions.

Investment costs. The cost functions for the propane HPs, BHEs and TES tanks were calculated based on literature [8,9], using a construction cost index of 1.11 for 2022 to extrapolate these to current price level. For EIWH and backup EH, typical costs were determined through internet research. A cost curve for ACHE was established based on literature values for products with a heat capacity range between 3 and 100 kW [10]. The installation costs for a façade-mounted LTDN were determined based on current planning values [11].

Safety Effort. The safety aspect evaluates the effort required for the safe operation of propane HPs in accordance with EN 308 or IEC 60335. Solutions that do not necessitate any external measures receive a rating of 5, while those with high additional requirements receive a rating of 1 [12,13].

External Effect (Acoustic/Visual). The assessment of external impact includes the number of visible components (outdoor units) and the expected noise emissions. A larger number of visible components negatively affects the visual appearance of the building and increases the likelihood of noise pollution, thereby impairing the overall assessment. The compressors are generally decisive for the overall sound power level of air source HPs, especially at high outputs [14].

3 RESULTS

Subsequently (Fig. 3 and Fig. 4) the rating scales of the studied system variants are shown as cumulated bar chart. The rating is relative between the studied system variants (central and decentralized separately) and ranges from 1 to 5 (lowest to highest). A high cumulated rating value is not necessarily the best solution for a given building, as the weighting of the single evaluation criteria may not be uniform.

3.1 Case study site with centralized heat pump systems

The SPF of the centralized HP systems ranges from 2.8 in system C5, which uses a centralized AWHP for SH and decentralized EIWHs for DHW, to 3.7 in system C3, which employs a centralized ground source HP and decentralized HIUs, as shown in Fig. 3. The SPF of ground source HP systems (C1 to C3) is higher than that of systems with a similar configuration using air source HPs (C5 to C6) due to the higher source temperatures. Systems using decentralized EIWH for DHW (C1 and C5) perform less efficiently overall than systems using centralized HPs for DHW, (C2, C3, C6 and C7), despite the elimination of circulation heat losses. The installation of decentralized HIUs positively affects the SPF due to the reduced temperature during storage and circulation, resulting in the highest SPF in system C3. The brine split system (C4) performs less efficiently than similar systems with outdoor monoblock AWHPs (C6) due to the additional heat exchanger.

The indoor space requirements range from 2 m^2 for system C1 and C5 to 6 m^2 for system C4. The rating scala in terms of indoor space requirement is nearly equal for systems with a similar configuration regardless of whether they use ground source BWHPs (C1 to C3) or monoblock AWHPs (C5 to C7). Although the monoblock AWHPs are installed outside the building, they require an additional TES tank for SH due to their higher rated output. Systems using decentralized EIWH for DHW (C1 and C5) requires comparatively the smallest space in basement because the DHW TES is no longer necessary. In contrast, the brine split system (C4) occupies more space for indoor BWHPs and TES tanks than any other systems due to its higher rated output.

The investment costs for installation and equipment per heated floor area in the building range from 59 €/m^2 for system C4 to 145 €/m^2 for system C3. The installation costs of BHEs for systems with ground source BWHPs (C1 to C3) negatively affect their rating scale in terms of investment costs. The impact of decentralized EIWHs and HIUs on overall investment costs is not significant. Although the brine split system (C4) performs least efficient in terms of energy and indoor space requirement, it has the lowest overall cost, as its cost for the BWHP is lower than that of outdoor AWHPs, and its expense for the ACHE is less than that of BHEs.

In terms of safety, the requirements for outdoor monoblock AWHPs (C5 to C7) can be met with comparatively less effort than those for indoor-installed BWHPs (C1 to C4) with a R-290 charge of more than 152g. However, the outdoor monoblock AWHPs (C5 to C7), which contain both the compressors and fans outside the building, receive the lowest rating regarding external effects. Since the compressors of the BWHPs (C1 to C4) are located within the building, their acoustic emissions are significantly reduced for the surrounding neighborhood. However, the rating scale of the brine split system (C4) decreases due to the outdoor ACHE.

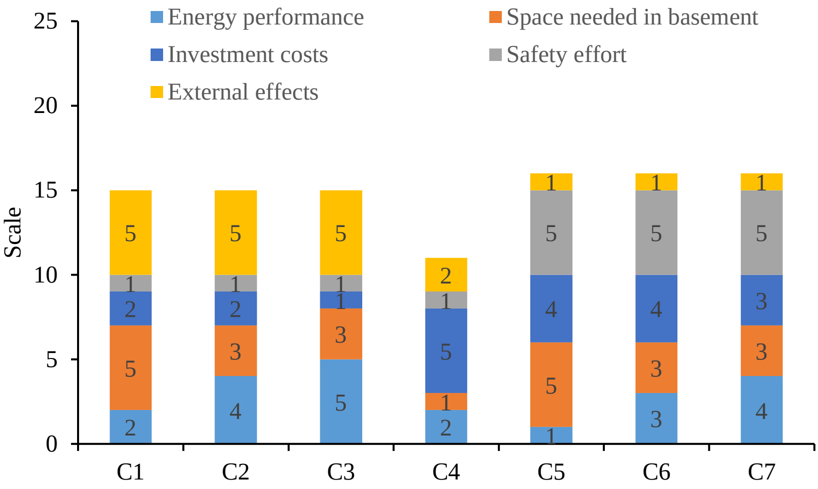

Fig. 3. Rating scala of the centralized propane heat pump solutions; 5: best, 1: worst.

3.2 Case study site with decentralized heat pump systems

Fig. 4 presents the rating scales of the decentralized propane HP solutions. The SPF of the decentralized HP systems ranges from 2.6 in system D2, which uses a decentralized brine split system for SH and decentralized EIWHs for DHW, to 3.6 in system D3 and D5, which employs a ground-source-based LTDN and decentralized BWHPs for SH and DHW. The decentralized AWHPs installed outside the apartments (D9 and D10) exhibit the second highest SPF. Systems with decentralized air source BWHPs, regardless of whether they are connected to an air-source-based LTDN (D4 and D6) or a decentralized ACHE (D7 and D8), show a nearly equal SPF. The impact of TES sizes on the overall SPF is not significant. The higher heat losses of the 120-liter TES tank (D5, D6, D8 and D10) compensate for the electricity used for backup EH.

The indoor space requirements corelate with the realizable product designs (see section 2.3) and are significantly affected by the sizes of the TES tanks. Systems using decentralized EIWH for DHW (D1 and D2) require comparatively the smallest space in the apartment because the TES is no longer necessary. Additionally, systems with decentralized monoblock AWHPs installed outside the building occupy less space in the apartment compared to systems with indoor-installed BWHPs.

The investment costs for installation and equipment per heated floor area in the apartment range from 269 €/m^2 for system D9 to 450 €/m^2 for system D5. The installation costs of ground-source-based LTDN (D1, D3 and D5) significantly increase their investment costs. In contrast, the total investment costs of all air-source-based systems with decentralized HPs vary slightly, regardless of whether they utilize air-source-based LTDNs, decentralized ACHEs, or monoblock AWHPs.

In terms of safety effort, systems D1 to D8, which contain hermetically sealed refrigeration circuits with a R-290 charge of less than 152 g, do not require any external safety precautions in accordance with applicable standards and receive the best rating of 5. Propane AWHPs typically have refrigerant filling quantities exceeding 500 g and require safety distances (e.g., to balconies and windows below) that are challenging to comply with on a MFH façade, especially in this case study site. Consequently, systems with monoblock AWHPs (D9 and D10) receive the lowest rating of 1 regarding safety effort.

The external impact is most negative for solutions with apartment-by-apartment development due to the large number of outdoor units and the associated risk of noise pollution. Therefore, the systems with decentralized outdoor monoblock AWHPs (D9 and D10) receive the lowest rating regarding external effects. Systems with decentralized ACHE (D7 and D8) are poorly rated as well.

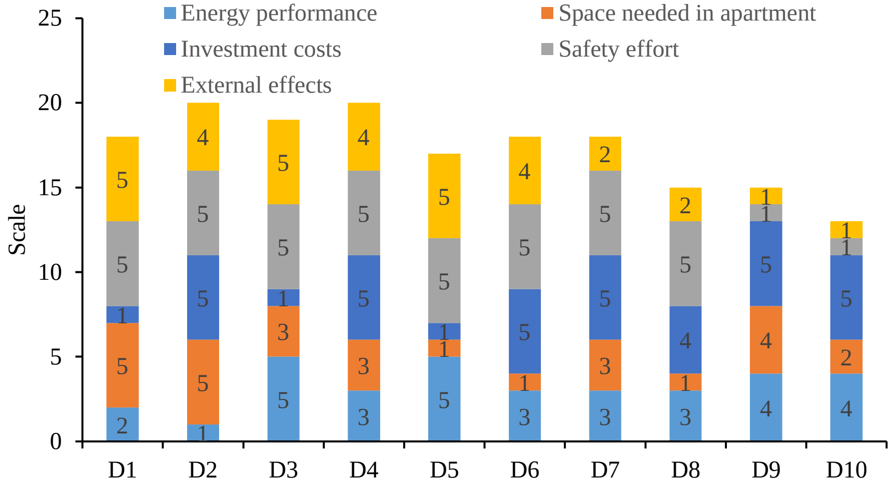

Fig. 4. Rating scala of the decentralized propane heat pump solutions; 5: best, 1: worst.

4 DISCUSSION AND CONCLUSIONS

This study shows that there is no single, universal propane HP solution for refurbishment due to the numerous, sometimes contradictory criteria that need to be considered in existing MFBs. However, there are several levers that can be used to adapt system solutions to different requirements.

For centralized heat supply, propane HP systems with higher heat capacity are increasingly available for both indoor and outdoor applications. This means that different boundary conditions such as source availability and installation area can be flexibly addressed.

Decentralized HIU for DHW should be considered to reduce circulation losses and increase overall efficiency. Prefabricated HP modules for outdoor installation could serve as a "game changer", significantly simplifying the implementation.
Compact propane HPs with less than 152 g of refrigerant seem to be feasible option for replacing decentralized gas boilers. DHW preparation is a challenge, particularly in terms of space requirement for TES tank. Small storage tanks in combination with an EIWH as a "booster" can represent a compromise between space requirement and efficiency.
For installation of monoblock AWHP systems on façades, compliance with the safety distance to windows and balconies can be limiting.

NOMENCLATURE

Acronyms	
ACHE	Air-cooled heat exchanger
AWHP	Air water heat pump
BHW	Borehole heat exchanger
BWHP	Brine water heat pump
DHW	Domestic hot water
EH	Electric heater
EIWH	Electric instantaneous water heater
HIU	Heat interface unit
HP	Heat pump
LTDN	Low-temperature distribution network
MFB	Multi-family building
SH	Space heating
SPF	Seasonal performance factor (including backup electric heater and electric instantaneous water heater)
TES	Thermal energy storage

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