Propane-based heat pump solutions for existing multi family houses – requirements and possible system solutions

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Abstract

Approximately 40% of the living area in Germany can be attributed to multi-family houses, a large share of which are existing buildings heated with fossil fuels. To decarbonize these with heat pumps, the housing industry needs standardized solutions for refurbishment. Therefore, this study compiles essential boundary conditions from the housing stock such as

- required capacity for heating and domestic hot water preparation
- required condenser outlet temperatures
- available installation space
- permissible acoustic emissions
- safety measures

On this basis three different heat pump solutions based on the future-proof low-GPW refrigerant propane (R290) are outlined:

- apartment-wise heating systems (currently typically consisting of wall-hung gas boilers)
- central heating systems, heat pump installed indoors
- central heating systems, air-source heat pump installed outdoors (direct evaporation)

Keywords: heat pump, multi family houses, requirements, heat sources, R290

1. Introduction

Heat pumps are expected to contribute strongly to decarbonizing residential space heating. The German government aims to have 6 million units installed by 2030, with continued installations in the subsequent decade. This ambitious goal necessitates a substantial increase in production, planning, and installation capacities. To achieve long-term greenhouse gas neutrality, it is crucial to avoid lock-in effects, especially regarding the choice of refrigerants. Therefore, natural refrigerants with low GWP should be utilized.

While heat pumps have become the favored heating technology in new single-family houses (SFH) in recent years and are increasingly common in existing ones, the existing stock of multi-family houses (MFH) still presents a challenge for this technology. High supply temperatures, limited installation space, and constraints in source availability in densely populated areas are significant barriers to its widespread adoption. Additionally, solid data on the performance of heat pumps in existing MFH is scarce. Lämmle et al. (2023) report seasonal performance factors (SPF, including backup heating rod, before buffer storage) of heat pump systems in small MFH from 1.5 to 4.7, averaging 3.5.

As a result, the majority of market-available products are designed for the SFH sector. Heat pumps with higher capacities (>15 kW) that use future-proof refrigerants and are specifically designed for refurbishing heating

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systems in MFH are limited (Oltersdorf et al., 2024a). To support new developments, the goal of this study is to compile typical requirements for heat pump systems in MFH and to derive generic solutions. Propane (R290) is the favored refrigerant in this context as it allows for high condensing temperature required for domestic hot water (DHW) preparation and bears no environmental risks such as high global warming potential (GWP=3) or persistent degradation products (PFAS).

2. Methodology

The compilation of requirements for propane heat pump solutions in multi-family houses is primarily based on literature research. This involves combining data from various sources to obtain clear and comprehensive information. The validity of these findings is cross-checked with stakeholders from both the housing and heat pump industry. To achieve this, an advisory board comprising over 15 heat pump manufacturers and 5 housing companies (collectively owning over 30,000 residential units) has been consulted in frame of the German development project LCR290[1]. For detailed case studies, six buildings from this stock have been selected as "example buildings," representing different scenarios and boundary conditions (such as central and decentral space heating, year of construction, urban environment, etc.).

3. Results

An extensive study on the availability of typical ambient heat sources has been conducted in recent years. Using simplified technical specifications of different source technologies combined with available GIS and statistical data, heat demands and source availability were determined for Germany. The resulting potential of promising low grade heat sources for heat pumps to supply the building stock is presented in Figure 1. This analysis does not differentiate between single and multi-family houses. Additionally, the results can only be regarded as indicative due to the simplifications in the methodology. Nevertheless, it becomes obvious that all regarded sources can contribute significantly. By including further sources, combining and adapting them, there is a good chance to increase the potential further.

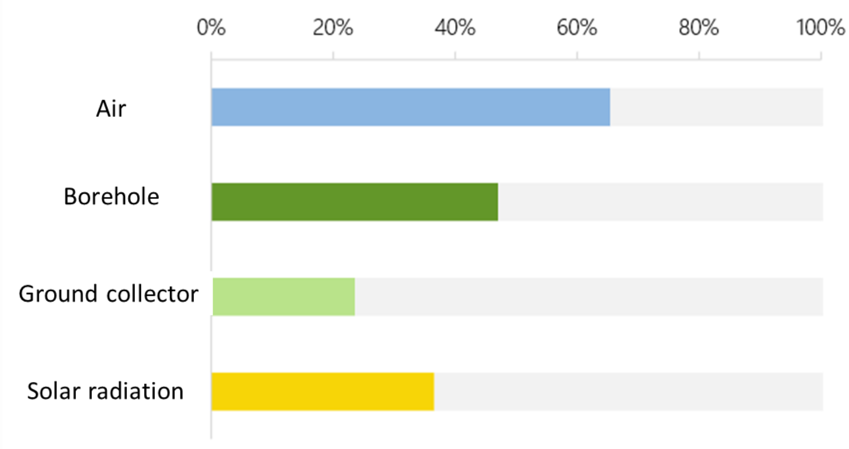

Figure 1: Share of residential building stock which can be supplied with heat pumps by sources according to (Greif, 2023)

3.1 Required heating capacities

3.1.1 Central heating systems

The basis for this analysis is a frequency distribution of buildings' areas based on data from the project partners' portfolio of buildings (see Figure 2 left). In total 3.3 Mio multi family houses exist in Germany. A crosscheck with the German residential building typology, which distinguishes by number of apartments instead of heated surface gives a good general agreement (Loga et al., 2015). Another basic

[1] https://lcr290.eu/

source is a frequency distribution of energy efficiency classes in German multi family houses which was gathered from the information of approximately 75000 energy certificates buildings (see right) (Krieger 2018). While the efficiency classes correspond to ranges of specific consumption (kWh/m²/a) an average (or typical) specific peak heating power (in W/m², defining the required capacity of the heating device) can be attributed to each of the energy efficiency classes. When the two sources are combined, multiplying the areas with the specific heating powers and weighting their occurrence accordingly a frequency distribution as shown in figure 2 results.

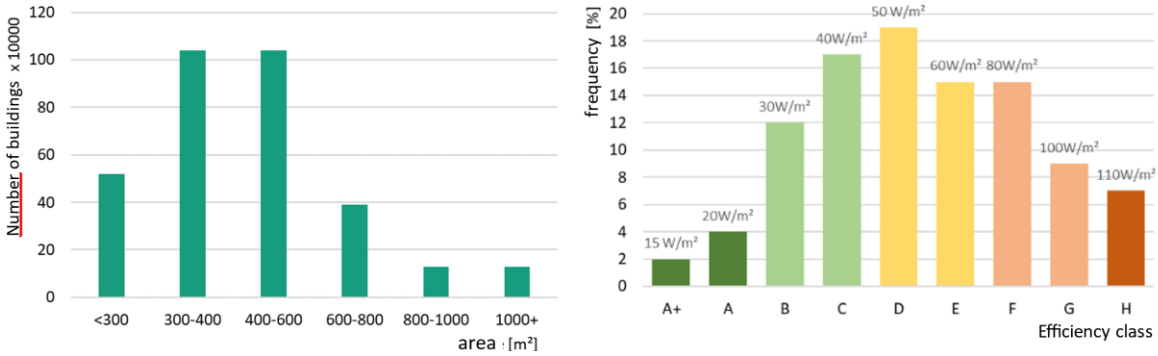

Figure 2: Data basis for an estimation of performance classes for central heat generators: the frequency distribution of flat sizes based on data from the project partners[2] building portfolio and the distribution of efficiency classes of multi-family buildings in Germany (Krieger 2018).

A large variety of heat pumps with R290 up to 15kW can be found on European market already. However, for the dominant capacity range of 16 to 35 kW the market availability of heat pumps is limited. Therefore, the recommendation is to concentrate on heat pump development in this capacity range. Higher capacities can be supplied by cascading various appliances.

3.1.2 Decentralized heating systems

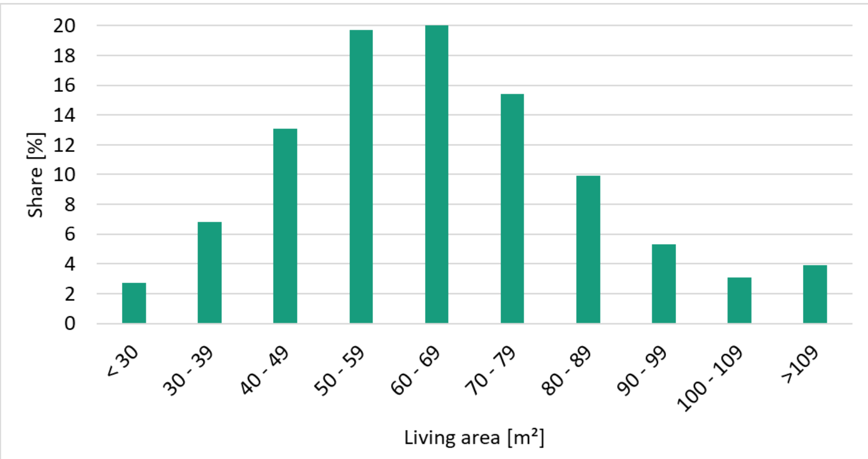

Figure 3: Frequency distribution of living areas in the German rental multi family house stock (Statistische Ämter des Bundes und der Länder, 2011)

A similar procedure as for the central heating systems has been applied to determine the required heating capacity of apartment wise decentralized heating systems. The frequency distribution of living areas in the German multi family house stock as shown in Figure 3 serves as data source in this case. Combining it with the efficiency classes and the related specific heating capacities yields (as in figure 2, right graph) a distribution

[2] The European Energy Performance of Buildings Directive 2010 requires buildings to have an energy performance certificate which specifies its final energy demand for heating and domestic hot water. Efficiency classes from A+ to H correspond to certain ranges of energy demand.

of required heating capacities as shown in Figure 4.

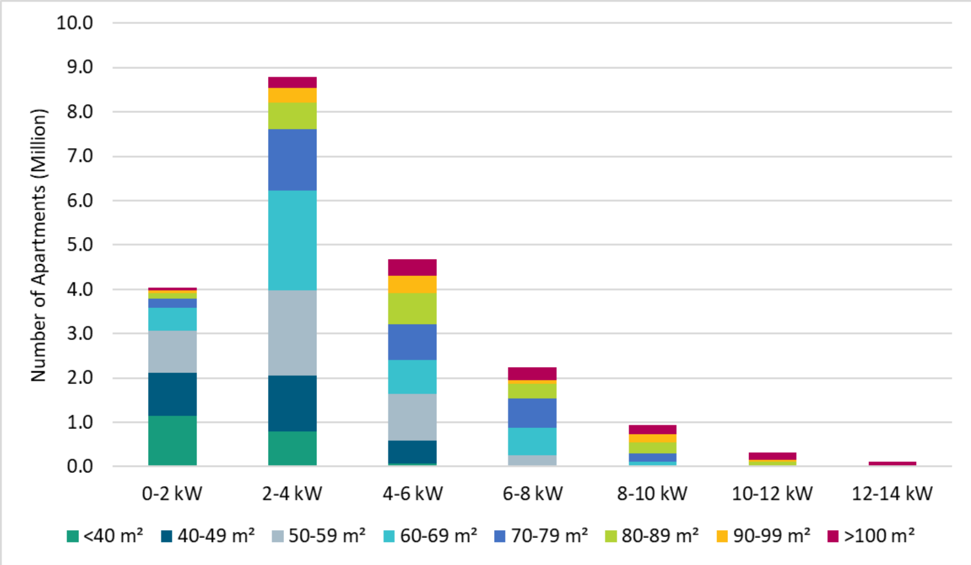

Figure 4: Derived frequency distribution of heating capacities of apartments in German multi-family houses

As a result, 60% of the flats have heating loads below 4 kW and 80% below 6 kW. Inaccuracies in this estimate result e.g. from

- the allocation of one average area-specific heating loads to each energy efficiency class, independently of the building size etc.
- the homogeneous application of the allocation of energy efficiency classes to all residential areas
- the fact that the frequency distribution of living space only relates to the rental housing stock

Nevertheless, it can be assumed that the majority of the housing stock has heating loads in the low to mid single-digit range.

3.2 Required hot water temperature

3.2.1 Space heating

Existing buildings in Germany and central Europe are typically heated by hydronic radiators. Typical design temperatures in existing buildings were 90/70°C (supply/return) or 75/65°C, which is the design point for radiators according to the European Standard EN 442-2.

To achieve decent seasonal performances with heat pumps which allow CO2-savings over fossil alternatives, a design temperature of 55°C has been found reasonable (Lämmle et al., 2022b). As radiators were oversized frequently in the past and based on a review of the radiator dimensioning of approximately 130.000 multi-family houses, it was estimated that the design heating supply temperature can be decreased to this value in approximately 50% of the German multi family houses without any adaptions to the distribution system (Techem Energy Services GmbH, 2023). In approximately 10% of the studied buildings the temperature could be decreased to even lower temperatures without the need for changes in the distribution system. The same study claims that another 40% of the stock can be refurbished to this temperature by a (partial) exchange of the radiators by products with higher capacity but the same cross section. An example for such a transformation is a building in Karlsruhe-Durlach (Germany), where the temperature could be decreased to 55°C from formerly 75°C by exchanging 7% of the radiators (11 out of 150) (Lämmle et al., 2022a).

3.2.2 Centralized domestic hot water preparation

To avoid the risk of legionella growth, central domestic hot water (DHW) systems in German multi-family houses need to supply a temperature of 60°C to all tapping locations (DIN 2012; DVGW 2004). The buildings also need to have a circulation line which prevents the cooling of the water (with subsequent potential legionella growth) in times without demand. The minimum temperature is required to be at least 55°C in the circulation return to the heat generator.

Typical system configurations for DHW preparation with heat pumps in MFH contain a storage to be able to cover peaks in demand. There is always a heat exchanger to separate the heating water circulating in the heat pump from the DHW. To overcome this heat resistance a temperature gradient is necessary, so a heat pump needs to be able to supply at least 65°C for such a system. A review of ~2500 market available heat pump models which received the Heat Pump Keymark (see (Jardin, 2024)) by (Lämmle et al., 2023) reveals that this required high temperature is a strong argument for using R290 as refrigerant. The median maximum temperature over the 94 listed products with this refrigerant is 70°C. The other common refrigerants R32 and R410A have median maximum temperatures of 55°C and 60°C, respectively (with 1478 and 818 listed products, respectively).

3.2.3 Decentralized domestic hot water preparation

DHW installations with a water volume of less than 3 liters between the heat generator and the most distant tapping location count as "small systems" in Germany (DVGW 2004). For these, there is no mandatory minimum temperature. 60°C are recommended and temperatures below 50°C "should be avoided" to hinder growth of legionella.

Yet, as space is limited in typical apartments with decentralized heating (see the chapter 3.3) and a substantial storage capacity is needed to cover demand peaks, it may not be possible to use this potential for decreasing the set temperature for heat pumps: the storage capacity is directly linked to its temperature. E.g. assuming a cold water temperature of 10°C, a tapping temperature for the DHW of 40°C and a perfectly mixed storage, decreasing its set temperature from 60°C to 50°C requires a 25% higher storage volume to achieve the same capacity. As the DHW will be prepared by heat exchanger, a temperature range up to 65°C is recommendable also for this application.

3.3 Available installation space

3.3.1 Centralized heat pump systems

According to current legislation in Germany for heating systems with a nominal output of more than 28 kW, the area of the installation room must be at least 7.5 m². The analysis of a small sample of MFH basement plan supplied by housing companies accompanying the project, proves that typical sizes are around 10 m² and no influence of building size can be observed (see Figure 5). As the buildings are typically heated with central gas boilers, which are compact up to a capacity of ~200kW, and DHW is provided by one central storage tank this is reasonable. The outlier with a surface of 32m² is a building heated by an oil boiler, so the area includes the space for a building integrated oil tank.

Switching to heat pumps will lead to a higher space requirement as the appliances themselves are larger and because systems are typically designed with higher storage volumes for robust operation and DHW supply. Additional space can typically be found in existing buildings' basements, possibly at the cost of reducing the size of the tentants' storage cellars. Therefore, new heat pump solutions should be compact and allow a wide modulation range to minimize the storage volume required for stable operation.

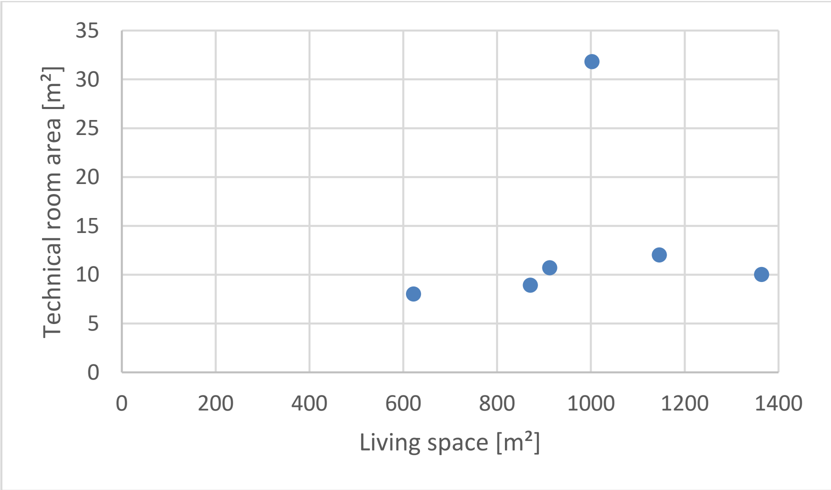

Figure 5: Area of 6 technical rooms compared to the heated living area in the sample buildings.

3.3.2 Decentralized heat pump systems

Wall-hung gas boilers typically have dimensions in the order of 450x750x350 mm (WxHxD). An overview of the dimensions of appliances from 7 manufacturers serving the European market is shown in Figure 6. In principle, the appliances can supply domestic hot water and heating without an additional storage cylinder. In some cases, however, they are installed with an additional domestic hot water tank in order to a) ensure comfort even when tapping at several points at the same time and b) enable simultaneous heating and domestic hot water utilization.

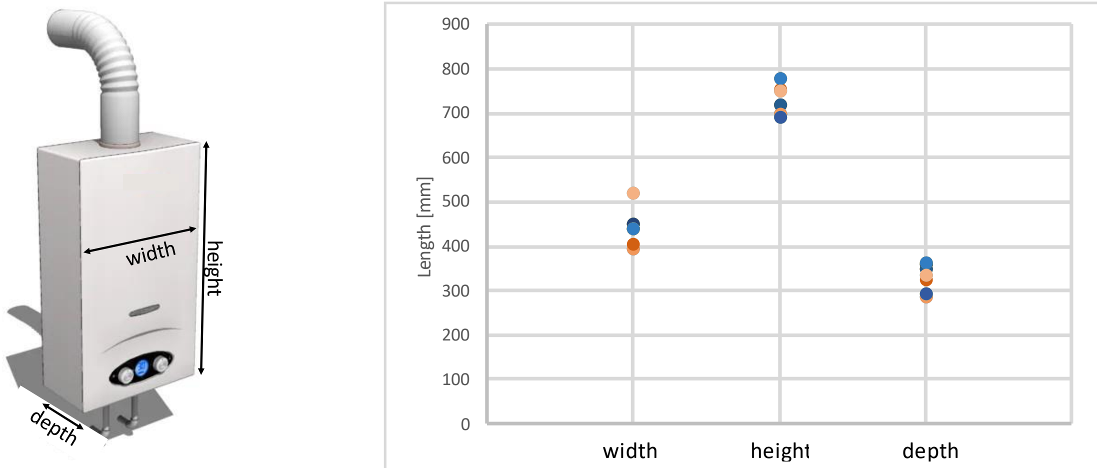

Figure 6: Dimensions of 27 wall-hung gas boilers from 7 manufacturers; only core appliance without hydronic, gas and flue-gas connections; source of image: Sketchup Warehouse

From the point of view of the housing industry, it would be desirable for heat pump solutions to have the same dimensions as a gas boiler. This is challenging due to the domestic hot water storage tank required for heat pumps. E.g. a storage for a 3-person household (a realistic number of tenants for an apartment with 50....70m²) requires a capacity of at least 82 liters if dimensioned according to EN 15450 and a set temperature of 60°C. The storages of market available heat pump systems suitable for apartments typically have higher volumes in the range of 120 to 180 liters. Therefore, the dimensions shown in Figure 7 should be considered.

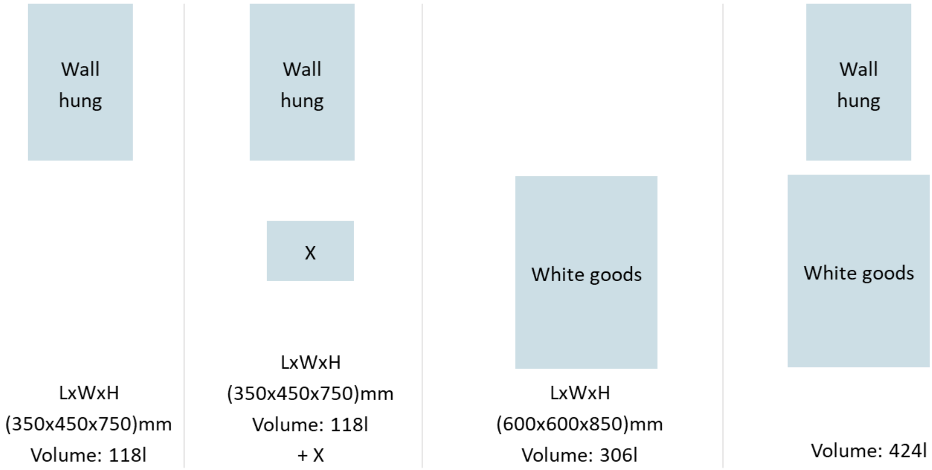

Figure 7: Design options of heat pump solutions for replacing decentralized gas boilers

3.4 Bivalence point of air source heat pumps

Multifamily houses typically have electric connection powers above 30 kW if design according to the corresponding standard DIN 18015-1, as illustrated by Figure 8. Above this value grid operators in Germany can pass part of the cost for extending the connection capacity to the owner(s) of the building. If a new electric transformation station is required to cover additional electricity load, the resulting costs can amount to several ten thousands of Euros. Therefore, the required connection power is relevant when switching to heat pumps.

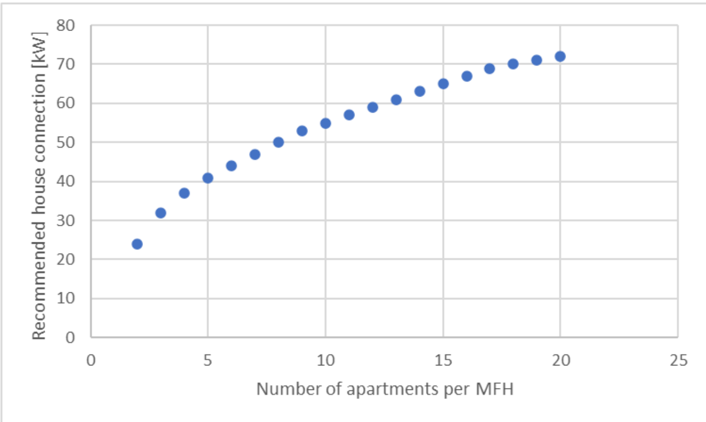

Figure 8: Recommended capacities for the electric house connection for MFH without direct electric DHW preparation according to German standard DIN 18015-1:2020 (DIN 2020)

The required connection power for a heat pumps system is primarily determined by the buildings heat demand and the bivalence point. The bivalence point defines the ambient temperature at which the heat pump reaches its maximum capacity. At lower temperatures it needs support of an (electric) backup heater to meet the heating load. A low bivalence point allows a high load coverage by the heat pump at the cost of a larger (and more expensive) appliance. The bivalence point also affects the required electric connection power for the heat pump system. Figure 9 visualizes this for an exemplary building with 25kW design heating load at -10°C ambient temperature. For a monovalent system (-10°C bivalence point) no backup heater is required. A typical air source heat pump which reaches 40% of the Carnot efficiency will require ~12.4kW electric power at this point (P_el_HP = P_el_sum; adopting the 55°C heating supply temperature from above, resulting in a COP of 2.02). As the bivalence point increases the required connection power also rises. E.g. a system with a bivalence point of -4°C will require a maximum of 16.6kW electric power (P_el_sum), half of which will be used by the direct electric heating rod (P_el_HR).

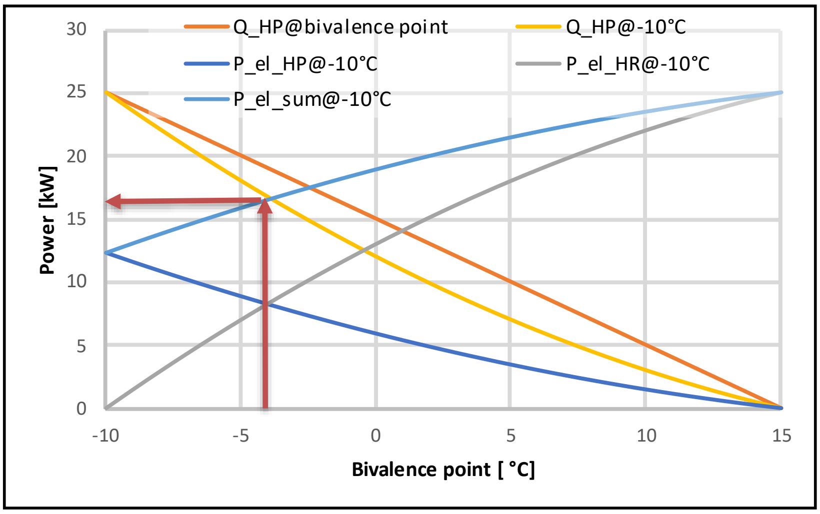

Figure 9: Influence of the bivalence point on the required electric power of a heat pump (HP), the backup heating rod (HR) and the resulting sum for an exemplary load case with 25kW design heat load at -10°C; Q: thermal power, P_el: electric power

Assuming that the 25kW design heat load corresponds to a rather average MFH with a living area of 500m², the frequently occurring energy class D (50W/m², see Figure 2) and is distributed over 8 apartments. According to the applicable standard for the dimensioning of the electricity supply this house should have an electric house connection of at least 50kW (excluding heat pump, see Figure 8). Assuming the electric connection was implemented exactly according to the standard (no over-dimensioning e.g. due to restrictions in available cable diameters) a monovalent heat pump with 12,4 kW electric power demand at -10°C will therefore need an increase of the connection power by 25%, the system with -4°C bivalence point even by 33%.

As the number of electric appliances increased in the past decades, the required connection capacity in older versions (the standard was first issued in 1955) may have been lower. Therefore, the relative additional capacity for heat pumps may be higher for older buildings.

3.5 Acoustics

This part focusses on indoor acoustics, as requirements on acoustics for air-source heat pumps placed outside the buildings are considered implicitly in chapter 3.1 (if restrictions on outside acoustic emissions are high, air is regarded as a non-available source).

Central heat pumps usually are not located inside an apartment, so it is not possible to actually specify limits for the heat pumps themselves. Limits typically apply for the immisions inside the inhabited space.

In the German standard DIN 4109-1989, a sound pressure level of max. 30 dB(A) in living rooms and bedrooms and 33 dB(A) in kitchens is recommended. For the wall-mounted gas boilers surveyed above, the sound power level is between 27 and 47 dB(A) at partial load and 41 and 52 dB(A) at full load. For wall-hung installation (hemispherical sound propagation), a sound pressure level 8 dB(A) below the sound power level can be assumed at a distance of 1 meter, i.e. between 19 and 39 dB(A) at partial load and 33 dB(A) and 44 dB(A) at full load. As living rooms/sleeping rooms are not generally used as installation locations for heat generators, 33 dB(A) is used as the target value for the sound pressure level at a distance of 1 m under nominal conditions. This corresponds to a sound power level of 41 dB(A) for the appliance.

3.6 Safety due to flammable refrigerant

As propane is a flammable refrigerant, specific safety measures apply for heat pumps with this refrigerant. For systems with a charge of maximum 152g, these can be solved by relatively simple measures such as hermetically sealed refrigerant circuit, as it is being done for typical household refrigerators in Europe. This approach seems feasible for decentralized heat pumps as first products on the market indicate. For higher capacities, safety measures need to be more extensive. A comprehensive overview can be found in a recently presented publication by Fraunhofer ISE (Oltersdorf et al., 2024b).

4. OUTLINE OF SYSTEM SOLUTIONS

Figure 10 visualizes major implementation options for (propane) heat pump solutions. These depend strongly on the heating system to be replaced. E.g. a central boiler will surely be replaced by another central heating solution, in our case a propane heat pump placed inside or outside the building. This decision is strongly influenced by the required safety measures on the one hand and the feasibility of air as heat source on the other hand.

Decentralized wall-hung gas boilers can either be replaced by decentralized solutions. This option is especially attractive if the refurbishment is not planned for all apartments at once but stepwise, e.g. only when the existing boiler breaks. Alternatively the building could switch to a central heating system, which implies major (and cost intensive) changes but may be attractive under the aspect of maintenance.

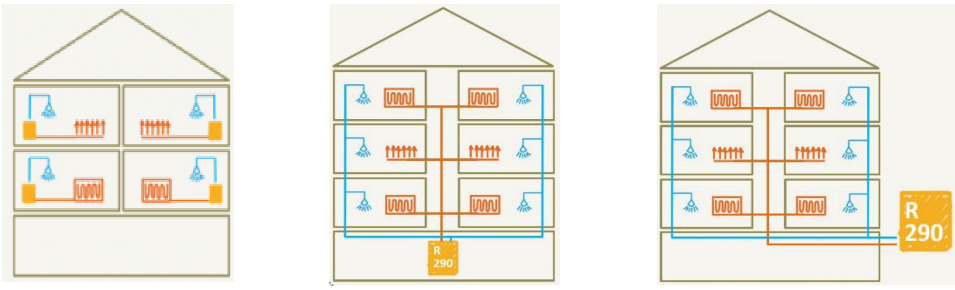

Figure 10: Left: decentralized heat pump solutions; center: central indoor heat pump; right: central outdoor heat pump; source: https://heatpumpingtechnologies.org/annex62/solution-matrix/

Table 1: Overview on possible options for implementation; A: Air, B: Brine, DHW: domestic hot water, HR: heating rod, HP: heat pump, HX: heat exchanger, SH: space heating, W: water, *: no or only few products available on the market with propane but development focus in the German project LCR290; ** no products available on the market with propane

Decentralized (~5kW)		Centralized Indoor (>25kW)		Centralized Outdoor (>25kW)	
SH	**DHW**	**SH**	**DHW**	**SH**	**DHW**
A/A-HP**	HR	A/W-HP*	HR	A/W-HP*	HR
A/A-HP**	as SH** (condensing storage)	A/W-HP*	as SH	A/W-HP*	as SH
A/W-HP	HR	B/W-HP*	HR		
A/W-HP	as SH	B/W-HP*	as SH		
A/B-HX + B/W-HP*	HR	W/W-HP*	HR		
A/B-HX + B/W-HP*	as SH	W/W-HP*	as SH		
Central source + B/W-HP*	HR	A/B-HX + B/W-HP*	HR		
Central source + B/W-HP*	as SH	A/B-HX + B/W-HP*	as SH		

Table 1 gives an overview on possible heat pump system solutions for the different options shown in figure 10. The availability of suitable heat pumps with propane as refrigerant is market with an asterisk. Only small capacity air-water products are available in significant amount[3].

The decision between the outlined solutions depends on many aspects, some of them shall be briefly discussed here:

- As space is very limited in existing apartments, it may be an option to only have a heat pump for space heating (SH) and prepare domestic hot water (DHW) with a direct electric heating rod. The negative implications are the much lower efficiency and thus higher electricity costs and the higher required electric connection power, which may not be available in existing buildings.
- Air-air heat pumps (multi-split systems) have low investment costs, can work efficiently in heating mode and also provide cooling in summer. Yet, their extensive installation may lead to problems with noise from numerous outdoor units, also maintenance is challenging. Additionally, indoor comfort may be affected by air circulation and noise from the indoor units; further on, split systems with propane are not really available on the market currently and all synthetic refrigerants currently used in systems below 12 kW will be banned by the F-gas regulation
- Small capacity B/W-heat pumps with R290 are currently being introduced on the market; they typically have a refrigerant charge below 152g and therefore require no complex safety concept (similar to household refrigerators, which typically use R600a/Iso-Butane as refrigerant in Europe)
- Small capacity monoblock A/W-solutions are readily available on the market; as the have refrigerant charges above 152g, they typically require safety distances from window openings and electric sockets; this may hinder their installation on facades/balconies. Brine-split systems, consisting of an air-brine heat exchanger installed outdoors and a B/W heat pump indoor, may be a workaround.
- Central heat pump solutions require higher heating capacities which lead to higher refrigerant charges. For systems using the flammable refrigerant propane this imposes additional safety measurements. As a consequence, heat pump manufacturers showed restraints concerning such products until now; one objective of the project LCR290 is the provision of generic and scalable safety concepts to overcome this limitation.
- Central DHW preparation requires the continuous circulation of water at temperatures above 55°C, as described in chapter 3.2.2. Especially in existing buildings the hot water piping may be poorly insulated which results in high losses. Therefore it may be an option to use central heat pumps for heating only and rely on direct electric heating rods for DHW – at the cost of a higher electric connection power.

5. CONCLUSIONS

In this paper we compile different categories of requirements for heat pumps for the refurbishment of multi-family homes. For central systems a heating capacity of ~30 kW at 55°C hot water temperature seems reasonable. For the replacement of wall-hung boilers in single apartments the capacity should be around 5 kW. As the existing fossil heat generators usually are significantly more compact than heat pump solutions which generally require larger storage volumes and space is limited, the development of compact appliances is recommendable. During system design it should also be considered that the electric power connection may be a limiting factor. An overview on possible system solutions with a brief discussion of their advantages and drawbacks is given.

[3] As of March 2024, the German list of heat pumps eligible for funding ("BAFA Liste") reports 324 R290 air-water heat pumps with a capacity up to 8 kW at A7/W55 but only 18 products with more than 25 kW.

6. ACKNOWLEDGEMENTS

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