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

Implementation and use cases of a compact, modular heat pump for residential buildings

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Abstract

The transformation of the heating sector towards climate-neutral heat supply poses a major challenge, particularly in the area of existing residential buildings. Heat pump technology can play a key role here. As part of the TEN.efzn research project, a compact, modular heat pump is being created that represents an integrative and intelligent system enabling flexible integration into different heating and domestic hot water systems and facilitating the replacement of fossil fuel heat supply systems.
Based on extensive research into building and heating system, eight practical use cases for single-family and multi-family houses have been defined. These cover centralised and decentralised supply solutions as well as considering typical building structures, renovation statuses and technical requirements. The analysis shows that there is great potential for compact, modular solutions, especially for apartment-wise heating systems.
A market analysis of current heat pump models shows that existing systems offer high supply temperatures and sustainable refrigerants, but are often not sufficiently modular or optimised for decentralised applications. The new compact heat pump should be designed during the TEN-project to fill these gaps and enable easy installation and broad applicability, as there is great market potential due to a significant need for replacement in the coming years. The defined use cases form the basis for further simulations, product design and component dimensioning.

Keywords: heat pump; existing residential buildings; use cases; plug and play heat pump; heat generator replacement

1. Introduction

Converting the heat sector from fossil fuels to a climate-neutral heat supply is a key objective of the energy transition under German legislation and European targets. In the existing residential building sector, the replacement of fossil-fueled heat supply systems represents a major challenge - this is where heat pump technology can play a key role.

Within the framework of the R&D project TEN.efzn, basic concepts and possible applications of a compact, modular heat pump, consisting of components from automotive thermal management, are being researched. One of the topics being analyzed is the extent to which automotive components can meet the requirements of the building sector in terms of energy efficiency, durability and safety. The standardization, modularity and compactness of the new heat pump module offers advantages for quick and easy installation or replacement of heat generators. This enables applications in different building types in terms of heating and domestic hot water.

Further information and insights into the idea and vision behind the compact, modular heat pump and the components planned for use as well as the boundaries and workflow for the simulation and design of the heat

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pump can be found in the IEA HPC 2026 papers ‘Compact, modular plug & play building heat pump using automotive components’ and ‘A holistic, simulation-based approach to integrating heat pumps into building energy systems’.

As part of the design process for the compact, modular heat pump, the first step is to define and establish the boundary conditions. In addition to the areas of application in various buildings and their supply concepts, the analyses include the selection of locations and weather data, low-temperature heat sources with their transfer systems (“Source”), and the installation situation and connection to existing systems (“use”) (Figure 1 (left side)). Furthermore, the technical aspects, legal and economic framework conditions are also evaluated. Market research was conducted to answer: Are manufacturers already on the market and are there areas of application in order to explore the potential for a novel concept for a compact, modular heat pump?

Another part is the implementation and manufacture of the compact heat pump (Figure 1, right side). This area involves, on the one hand, the design of power electronics using different materials as semiconductors (GaN, SiC) to improve efficiency and component size, and on the other hand, the use of components from the automotive sector as well as the use and integration of natural refrigerants (R290, R744). Finally, research is being conducted into fault detection and optimization as well as intelligent control of the heat pump (AI, G^{-1}, PID).

The paper focuses on defining building integration and the supply concept within the building for the heat pump, thus representing a partial section from the overall analysis and determination of the boundary conditions and limitations for the plug&play heat pump during the project TEN.

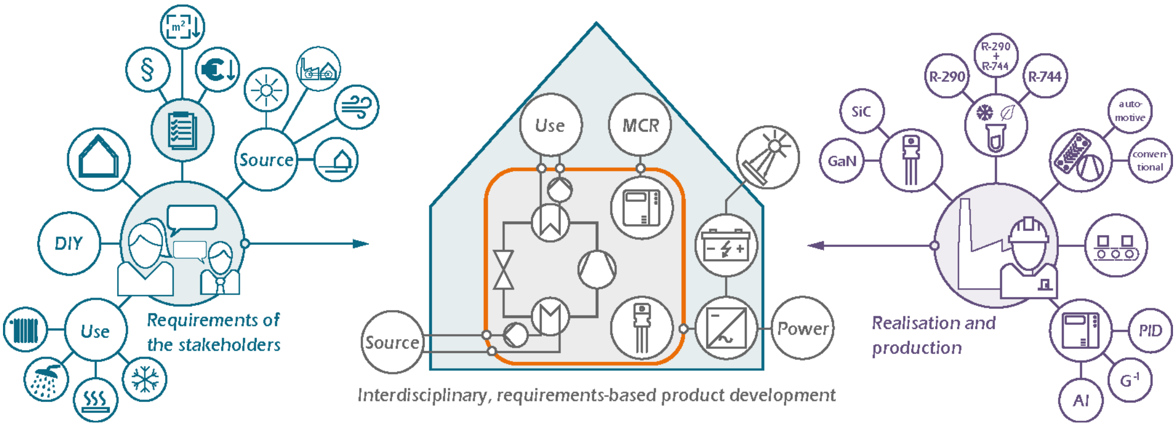

Figure 1. Vision of a compact, modular plug&play heat pump for residential use - influences and boundary conditions

2. Research and analyses of building types and heating systems

Based on analyses and research into building and heating system typologies, relevant use cases are defined as application scenarios for the compact heat pump modules. Relevant use cases would include, for example, replacing gas heating systems in apartment buildings, supplying single-family houses or, more generally, supplying existing residential buildings.

The research relates, among other things, to reference buildings (existing buildings) with renovation standards, necessary technical constraints, market relevance with an examination of the market situation for heat pumps, practical relevance in terms of fields of application, and implementation examples.

Characteristics relating to floor plans and room layouts, etc. from reference buildings already developed for other projects [1][2] were also considered within the design of the reference buildings. When working out the use cases and possible building types, existing building data and floor plans were used as a basis, along with research projects and other templates. At the start, the focus was on developing a region-specific reference building, such as an archetypal multi-family house (MFH) or single-family house (SFH) in Lower Saxony. However, it was subsequently decided to present the approach using a general average building for the whole of Germany.

2.1. Building type and heating system

For the selection and analysis of the use cases, the first step was to collect the requirements and boundaries with regard to the building and the integration of the heat pump into the already existing supply concept. The key data for the use cases and the survey of the building stock include:

- Building types (residential buildings)
- Building age structure/construction age classes and renovation status
- Heating area [m²]/apartment size [m²]
- Existing heating system (room system) (radiator, underfloor heating, etc.)
- Generator location (centralized or decentralized)

The analysis evaluated more than 130 sample projects (old heat generators already replaced by heat pumps) as well as existing statistics and reports for Germany's building stock (see all references; especially [3-10], [20]). Since many of the sources evaluated focus primarily on SFH a large number of SFH are included in the evaluation.

The research and evaluation of the documents reveal both, the greatest needs as well as building occurrences in the following areas: (Figure 2 to Figure 4)

- Building type/residential structure: SFH and MFH
- Number of flats in MFH: 3 to 6 or 7 to 12 residential units
- Flat size (average): in MFH 60 to 80 m² and in SFH around 130 m²
- Age of building: 1950 to 1980
- Renovation standard for buildings constructed between 1950 and 1980: medium modernisation standard, which means that energy-efficient modernisation work has already been carried out on some or several components or component areas.
- The specific final heat consumption for space heating and domestic hot water in buildings constructed between 1950 and 1980 is 170 kWh/m²a for SFH and 135 kWh/(m²a) (100 – 150 kWh/(m²a)) for MFH.
- The heating system in buildings constructed between 1950 and 1980 primarily consists of static radiators with average heating supply temperatures of 40 – 50°C (operation not dimensioning).
- Location of the heat generator: centralised or decentralised.

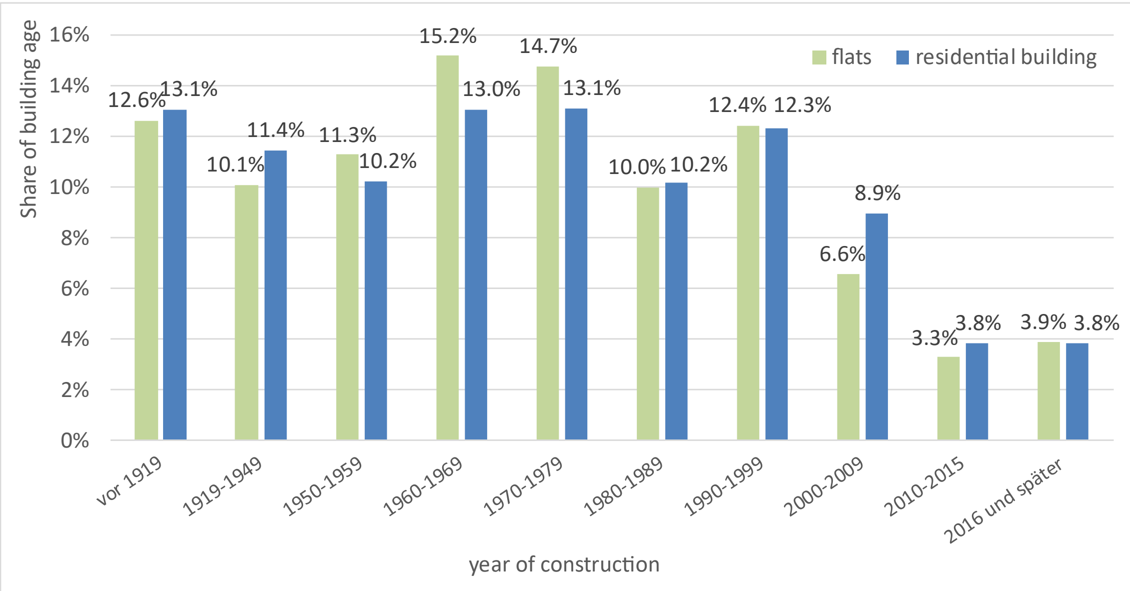

Figure 2. Building age of flats (green) and residential buildings (blue) in Germany [10]

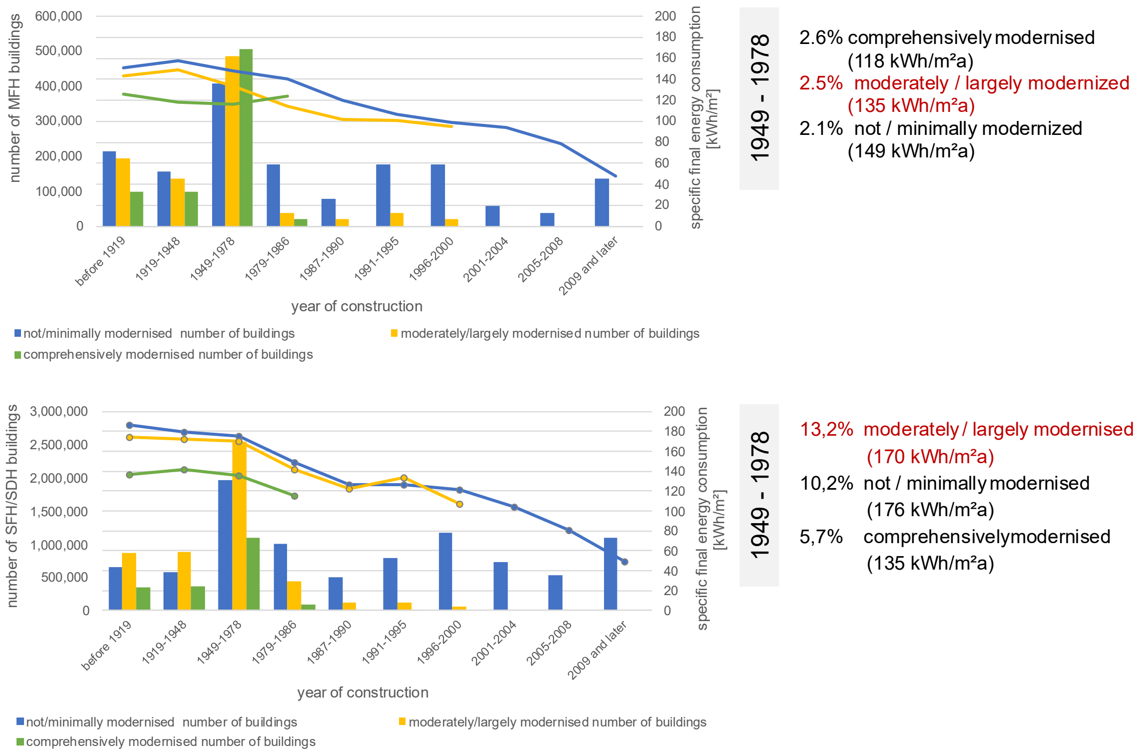

Figure 3. Development of building standards in Germany for MFH (above) as well as SFH / SDH (below) [6][11]

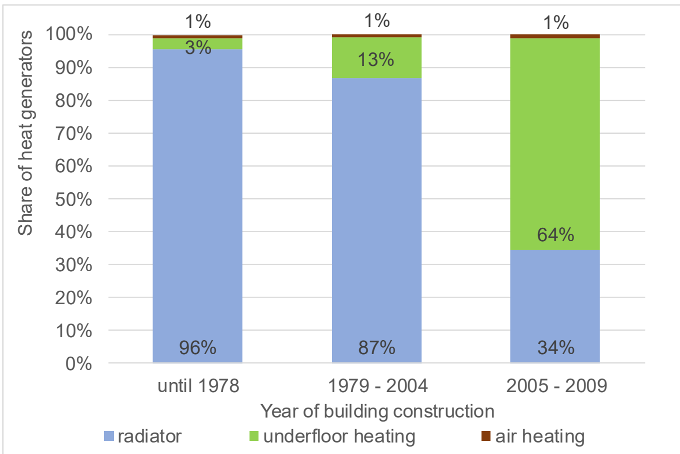

Figure 4. Heat transfer systems in residential buildings of different age groups [3] [12]

2.2. *Heat supply concepts for heat pumps in residential buildings*

Based on the heat pump concepts of IEA-HPT-Annex 50 [13] (Figure 5) the existing/identified supply concepts in the reference buildings or statistics from the research were broken down.

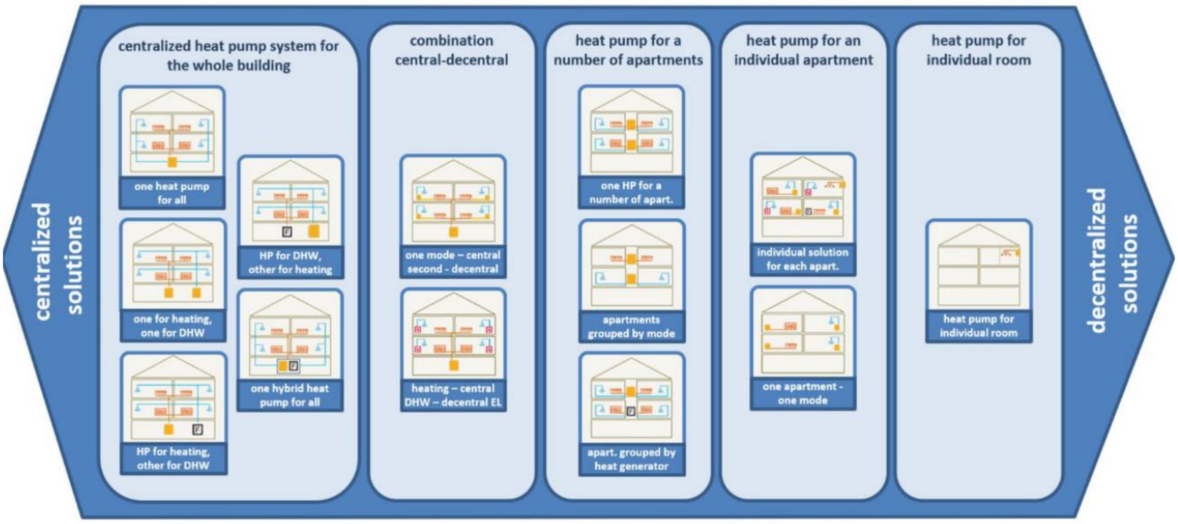

Figure 5. Overview of 13 heat supply concepts utilizing Heat Pumps sorted by families according to their degree of system centralization [13]

The defined heat pump types can be divided into decentralised and centralised solutions. Decentralised solutions are used in MFH as apartment-wise heating systems, thus providing an individual solution for each flat.

The following variants were selected for further selection and as use cases for the compact, modular heat pump based on the example projects and research: (Figure 6)

central solution … decentralised solutions

from the building (inc. SFH) … … to apartment-wise supply

		description
1.1	central heat pump	both space heating and domestic hot water heating are provided by a heat pump
1.2	central heat pump	separate heat pumps for space heating and domestic hot water preparation
1.3	central heat pump plus central auxiliary generator	WP for space heating and additional generator for domestic hot water heating
1.5	central hybrid supply	combination of a heat pump and another generator, with both generators ensuring the supply of space heating and domestic hot water.
2.2	central heat pump and decentralised DHW preparation	WP for space heating and decentralised, electric domestic hot water heating
4.1 a/b	decentralised solutions	individually controlled solution for every flat for generating space heating and domestic hot water heating

Figure 6. Selected heat pump types for SFH and MFH within the scope of the application analysis

3. Market positioning and potentials of the compact heat pump

The evaluation of the German Zensus 2022 on heat supply [10] in residential buildings shows that central heating systems are predominantly used in buildings – 81 % in relation to buildings and 70 % in relation to flats. District heating and apartment-wise heating systems each account for 6% in residential buildings and 15 % and 9 % respectively in flats. (Figure 7; left) The bdew report [14] [15] provides an overview of average age of the heating systems and the type of heating (gas central heating, gas apartment heating, oil central heating, district heating and individual heating), which also includes the distribution to the individual federal states. TEN.efzn focuses on Lower Saxony, although the demand in the use cases to be determined is extrapolated to the whole of Germany. The distribution of heat generators for the existing buildings in Lower Saxony is 64 % gas/oil central heating, 15 % gas apartment heating and 9 % district heating (Figure 7; right). In addition to SFH and central heating solutions, a compact solution must be found for apartment-wise heating systems in particular, which can be seamlessly integrated into different heating and hot water systems and thus, in the best case, also enable flexible replacement on a flat-by-flat basis. The compact, modular heat pump can fill these gaps and exploit this potential, among other things (as one module or as combination of multiple modules).

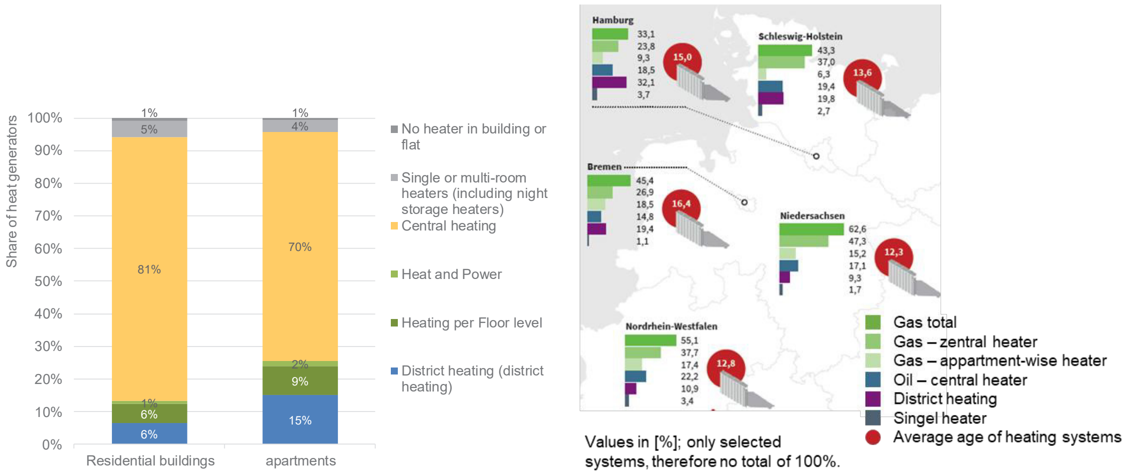

Figure 7. Type of heat supply in existing residential buildings across Germany [10] (left) and across the individual federal states [14] (right)

The following section examines the sales figures for heat generators in Germany since 1998 that are powered by gas, oil or biomass. According to the German law (GEG), heat generators must be replaced after 30 years of operation at the latest. Consequently, a heat pump could then be installed to replace them. (Figure 8)

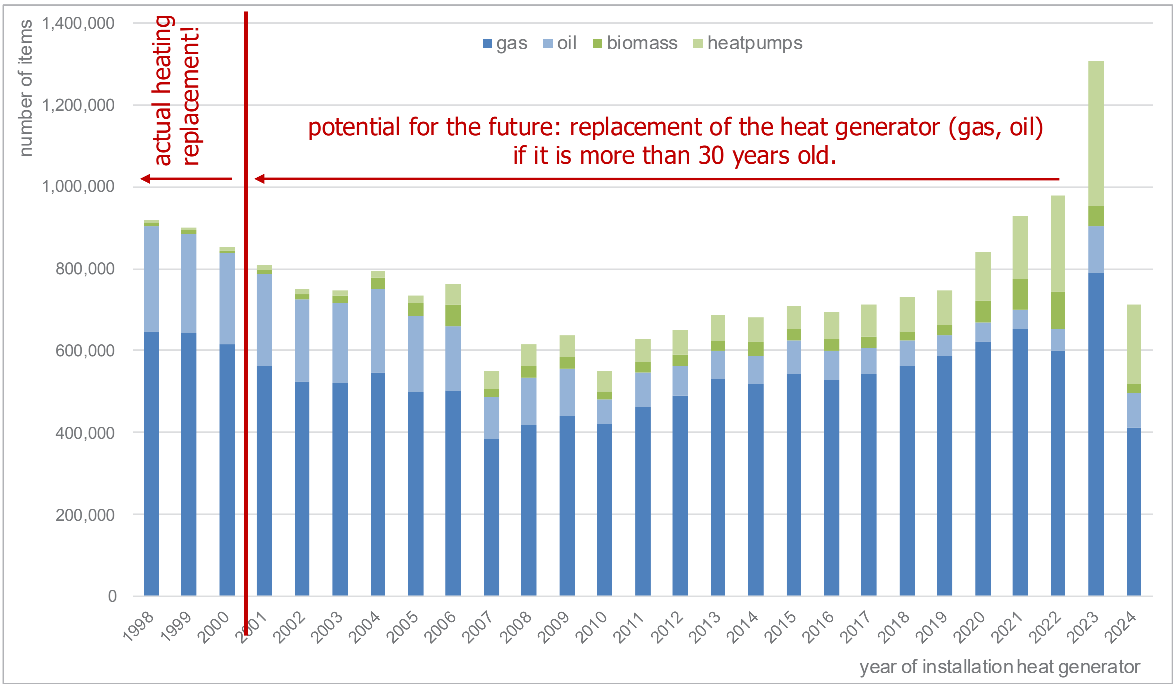

Figure 8. Expected number of heat generator replacements based on current sales figures for the years 1998 to 2024; (own illustration according to [8], [16], [17])

In order to develop practical, meaningful and relevant use cases for the heat pump module in residential buildings, a market analysis of similar heat pumps (fulfill the use cases) already on the market was carried out in parallel with the identification of use cases/application scenarios. The focus was on heat pumps that are also described as ‘(gas boiler) supplier replacement’, ‘compact heat pumps’ and ‘public heat pumps’, and have a maximum heating capacity of 12 kW (max. heating capacity range of one target heat pump module). The parameters examined included the heating capacity range, heat sources to be connected, refrigerants used and maximum achievable supply temperature (in the case of standard design), as well as the size and weight of the heat pump. The aim of the survey was to differentiate the compact, modular heat pump from existing heat pumps already available on the market and to integrate it into existing technological requirements and solutions. In addition, the aim was to gain an overview of the current market situation, developments in the heat pump sector and further potential.

Around 40 models from nine manufacturers were identified.

- Most of the heat pumps surveyed (70 %) achieve a supply temperature of 75°C and can therefore be used for domestic hot water preparation. Manufacturers' specifications for maximum supply temperature range from 45 to 75°C (Figure 9).
- Of the heat pumps available on the market, 74 % are air-to-water heat pumps, 21 % are brine-to-water heat pumps and 5% are water-to-water heat pumps. (Figure 9)
- 77 % of the heat pumps surveyed use propane (R290) as a refrigerant. R32, R410A and R513A are also used. (Figure 10)
- The majority of heat pumps achieve heating outputs of 3 to 6 kW at the design points. (Figure 10)
- The size (volume) of the indoor units ranges from 0.04 to 2 m³ and the weight is between 35 and 200 kg. (Figure 10)

Based on market research results, the initial conditions and requirements for the compact heat pump were defined in order to be competitive and ‘innovative’ on the market. In Figure 9 and Figure 10, the initial targets defined for the implementation of the heat pump are marked with a red frame.

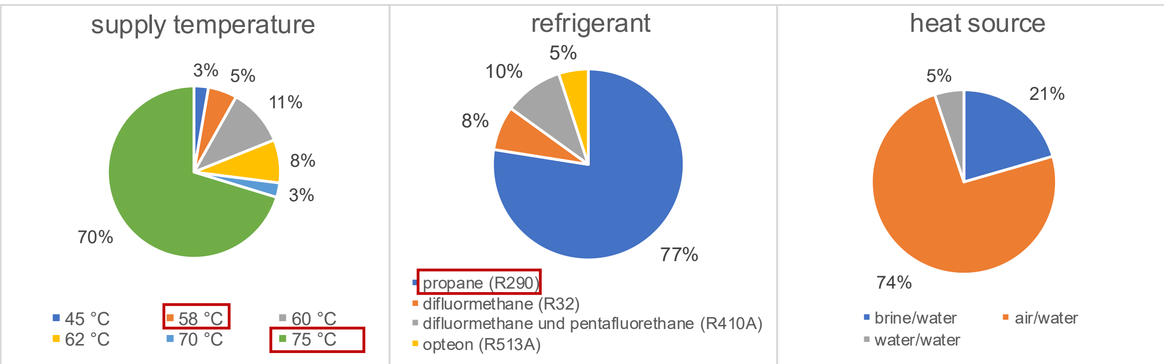

Figure 9. Market research on heat pumps: achievable supply temperatures (left), refrigerants used (centre), connectable heat sources (right); red mark = target module requirement

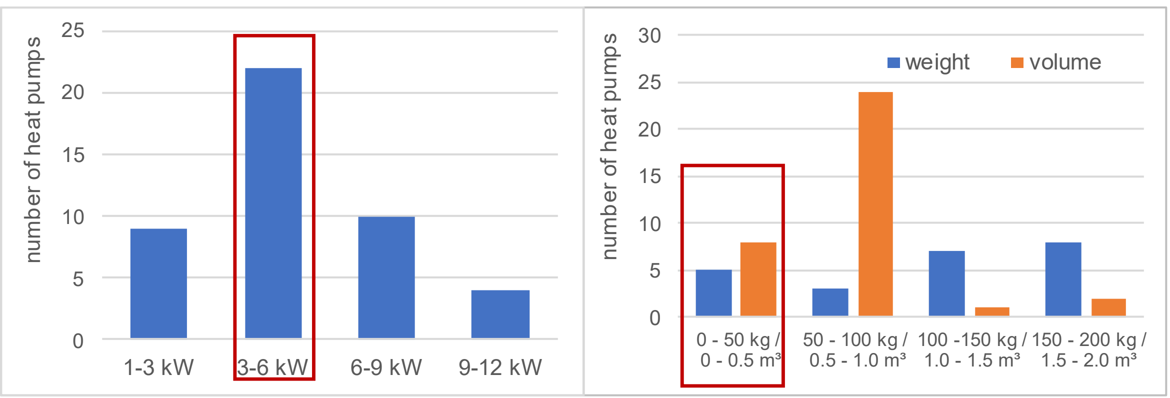

Figure 10. Market research on heat pumps: heating capacities (left); weight and volume of the indoor module (right); red mark = target module requirement

4. Use cases for the compact heat pump

The overall objective of the project is to design an integrative and intelligent heat pump module with standardized connections through requirements-based and interdisciplinary research, which can serve the defined applications. The designed heat pump should integrate seamlessly into different heating and hot water systems, thereby reducing complexity for planners and users.

The evaluation results in eight relevant use cases or typical application scenarios for the compact, modular heat pump (Figure 11). The definition and derivation of the use cases is based on the research and results presented in Chapters 2 and 3.

The eight cases comprise three cases in SFH and five cases in MFH. In the variants for MFH, both centralized and decentralized placements are considered. The variants are also formed by the distinction between supply concepts. The heating case of room heating via the heat pump as well as the combination of room heating and domestic hot water are considered.

With regard to the transfer system (radiators), a maximum flow temperature of 40 – 50°C is currently assumed for the design (assumption: radiators are designed for the required demand and temperatures). The flow temperature forms the target value for the design of the heat pump and the required heating output.

In addition to the main criteria, additional variants can be defined, which will be considered in the further course of the project and for which additional boundary conditions are taken into account:

- Cooling of flats and buildings
- Integrated buffer storage tank
- Underfloor heating instead of static radiators to achieve a lower supply temperature
- Demand-driven supply temperature control vs. heating curve

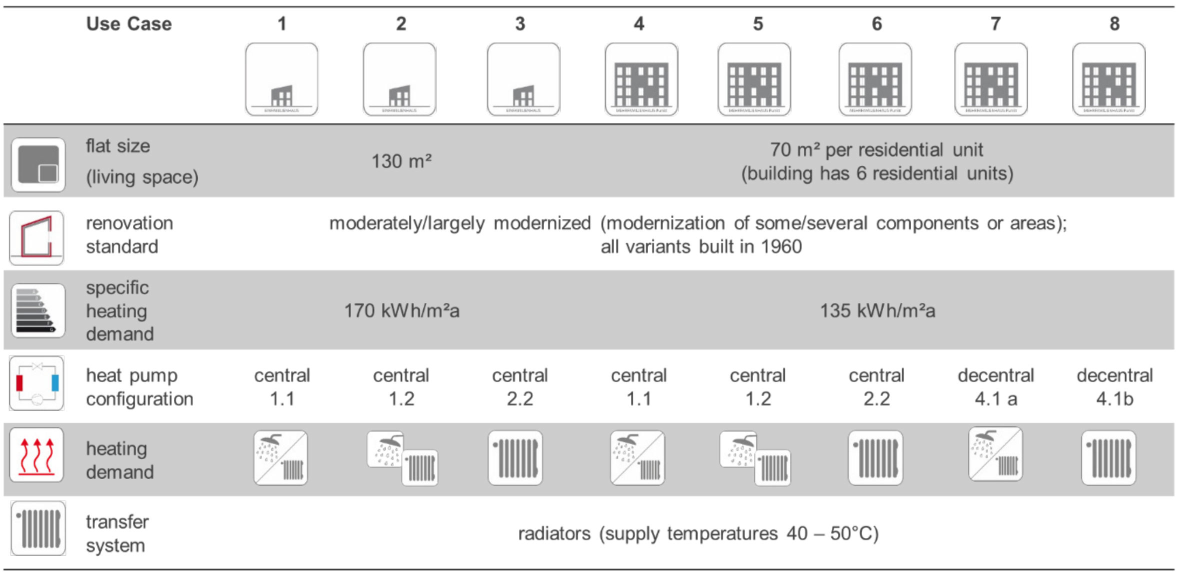

Figure 11. Derived use cases for further processing and simulations within the framework of TEN

5. Consideration of locations

The defined use cases are intended to determine the annual specific heating demand and the annual total heating demand for the selected building types and supply concepts in Germany. In order to determine the required heating output of a heat supply system, the standard heating load is usually calculated in accordance with DIN EN 12831-1:2017-09 [18]. This standard defines the design heating load (maximum heating load) at a specific standard outdoor temperature, e.g. without the influence or gains from solar radiation. In practice, this design approach often leads to oversized heat pumps, which can have a negative impact on both the efficiency and service life of the system [1] [12].

In order to determine realistic heating capacities for a single heat pump module and to dimension the components of the heat pump, annual heat demand profiles of the application cases from thermal building simulations with TRNSYS are used [19]. Simulations provide more realistic representations of heating demand, as they capture not only the maximum heat output required, but also the temporal distribution of heating loads throughout the year. By taking into account both the maximum load and the load distribution, the heat exchangers and, in particular, the compressor of the heat pump can be designed to meet demand.

The 15 test reference regions of the German Weather Service (DWD) (also known as TRY15 regions) are traditionally used for thermal simulations. These divide Germany into 15 geographically contiguous regions with similar weather characteristics.

However, it is not the weather data itself that is of interest for the design of thermal systems, but rather parameters derived from the weather data that influence the design and operation of thermal systems. For this reason, the project plans to conduct further studies and evaluations regarding the location.

In the next steps a weather data set updated by the DWD is combined with population data from the Zensus database and transformed from a 1 x 1 km grid resolution to the municipal level. [21] [22] The following four parameters should be used to identify geographical areas with similar climatic requirements for the design and operation of heat pumps:

- Heating degree days
- Global solar radiation during the heating period
- Minimum outside temperature during the heating period
- Potentially freezable water content of the ambient air

Using the elbow method and the silhouette score, the number of clusters should be defined to ensure a good balance between information gain and computational effort. After clustering, a grid point is extracted from the raw data of the DWD for each cluster, which most accurately reflects the cluster means of all cluster parameters. The grid point extracted in this way serves as a reference location or weather boundary condition for the creation of the heating load profiles. The result is a number of annual heating load profiles, which representatively show the weather-related requirements for the design and heating operation of the heat pump.

6. Conclusion

The transition of the heating sector from fossil fuels to a climate-neutral heat supply is a key objective of the energy transition – both within the framework of German legislation and European requirements. Replacing fossil fuel heating systems poses a major challenge, particularly in existing residential buildings. Heat pump technology can play a decisive role here.

The TEN.efzn research project and in particular the research platform "heat" is investigating fundamental concepts and potential applications for a compact, modular heat pump consisting of components from automotive thermal management. One focus is on the extent to which these components can meet the requirements of the building sector in terms of energy efficiency, durability and safety. The standardisation, modularity and compact design of the new heat pump module offer advantages for quick and easy installation or replacement of heat generators. This opens up a wide range of possible applications in different types of buildings – both for space heating and for the provision of hot water.

In a first step, it was necessary to define key constraints and identify areas of application in different building types and supply concepts.

A market analysis identified key technical and functional features of current compact heat pumps and provided a clear picture of the current situation on the market. It showed that there are already systems that combine high supply temperatures of up to 75°C, compact designs and the use of natural refrigerants such as propane (R290). Nevertheless, the research also shows that these systems are often not yet sufficiently optimised in terms of their modularity, flexible integration and suitability for decentralised applications, especially for the replacement of apartment-wise heating systems in building stock.

The findings provide a solid basis for tailoring the development of compact, modular heat pumps to existing market gaps and future requirements. The potential of decentralised solutions should be emphasised here. These could be particularly important for owners' associations or individual apartment users who want to gradually switch to environmentally friendly heating technologies.

At the same time, analysis of heat supply structures shows that the vast majority of German residential buildings have centralised heat supply systems. Given the large number of heat generators (> 40,000 per year) due for renovation in the coming years, there is a need to develop a modular system that can accommodate both centralised and decentralised applications. Only such a flexible system architecture can ensure broad applicability in different building configurations.

Based on the identified building and heating system structures, boundary conditions for the system design were derived. These formed the basis for the definition of eight representative use cases that reflect real building typologies, heating systems and renovation statuses. These scenarios take into account both centralised and decentralised supply solutions for SFH/MFH and thus form the starting point for further research and development.

Based on the defined application scenarios, the next step in the research project is to create TRNSYS building models in the simulation environment. The simulation models are then used to create load profiles for the heat pump in two steps: First, a building simulation model is developed that maps the respective application case. Next, weather data is processed and clustered in order to expose the building simulation model to external climatic influences. By combining the simulation model with the weather data, realistic heating load profiles will be created.

Nomenclature

abbreviation	meaning
AI	Artificial Intelligence
DWD	German Weather Service
ST	Supply Temperature
G^{-1}	Mathematical description of a transfer function of controlled systems or controlled system elements; describes the dynamic behavior of the system; high -1 is then used, for example, for disturbance compensation.
GaN	Gallium nitride
GEG	GebäudeEnergieGesetz / Building Energy Act
HP	Heat pump
MFH	Multi-family house
MCR	measuring, controlling, regulating
PID	Proportional-integral-derivative controller
R290	Propane
R744	Carbon dioxide
SDH	Semi-detached house
SFH	Single-family house
SiC	Silicon carbide
TRY	Test Reference Year

Acknowledgements

The Projekt “TEN.efzn – Transformation of the Energy System in Lower Saxony” is funded by zukunft.niedersachsen, the joint science promotion program of the Lower Saxony Ministry of Science and Culture and the Volkswagen Foundation. The authors thank the ministry and project partners for funding and support. Responsibility is assumed by the authors for the content of this publication.

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