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Fields of application of large-scale heat pumps and challenges in planning

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Abstract

Large-scale heat pumps are increasingly used in the heat supply. The challenge in creating a heating concept for the use of large-scale heat pumps is the balance between cost efficiency and CO_2-emissions. certain criteria such as the innovation of supply concept and technologies, the reduction of CO_2-emission and the acceptance as well as the cost-effectiveness must be taken into account in advance. Heat pump systems and concepts on this scale require appropriate design and pre-planning.
Large-scale heat pumps have the potential to be used in many different ways. In this paper, five examples of heat pump integration will be presented, from neighborhoods, building blocks and the use of waste heat for district supply. These projects show that a significant contribution can be made to increase the share of renewable energy in the heat supply. It can be shown that it is theoretically possible to cover the heat demand up to 100% via the application of heat pumps. Furthermore, enormous ecological potentials can be demonstrated. Compared to gas boilers, CO_2 reductions of 50 - 90% can be achieved.

Keywords: large-scale heat pumps; energy concepts; planing and design; examples

1. Introduction

On average, each person in Germany emits around 7.75 t of CO_2 per year (energy-related – electricity and heat, 2019) [1]. An emission per person of less than 1 t CO_2 per year would be climate compatible [2]. This shows that sustainable consumption requires great efforts and a reduction of around 90 % compared to the current level. A major contribution to achieve climate neutrality can be achieved by reducing emissions in the residential sector. Here, heating offers large potential. Energy consumption must be reduced in the long term, e.g. through thermal insulation of the building envelope. The same time there must be a coupling of the heat and electricity sector, as electricity can more easily be replaced by renewable energy. This coupling can be achieved by using heat pumps.

These positive effects of heat pumps can be scaled up if they are integrated into district heating grids. This can result in modern supply concepts, where smart controllable large-scale heat pumps are integrated for energy-efficient operation. However, these systems face many challenges. Suitable environmental heat sources for the residential energy supply must be dimensioned and developed to the required extent. For resilient and cost-efficient operation, heat pumps may need to be used bivalently in combination with other heat sources of the heating grid. The difference in temperature levels required for new and existing buildings connected to the network needs to be considered.

Such supply concepts should be developed holistically together with the electricity sector. The integration of heat pumps results in a high level of electrification, which should be covered by renewable electricity. Furthermore, the energy concept must enable the energy supply in the neighborhood with the highest possible share of renewable energy at economically justifiable investments and operating costs. In order to consider the costs of the project holistically, land acquisition, grid connection costs and general development costs must be

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taken into account. The transferability of the energy concept to other projects depends strongly on the existing infrastructure and the specific requirements of the residential area, which often results in individual solutions.

To sum up, for designing and choosing an energy supply system for districts, certain criteria have to be met:

- Innovation (using innovative technologies and supply concepts)
- Renewability (including reduction of carbon dioxide emissions)
- Resilience (against internal and external disturbances)
- Potential for servicing the electricity grid
- Transferability (of the system design to other districts / cities)
- Acceptance (among the local population)
- Economic efficiency

The framework conditions and prerequisites for the integration of large-scale heat pumps into supply concepts are given. In addition to the actual concept, the technical components are also available. In addition to the already existing use in the metal processing industry and the food industry, the application area "district heat supply" is seen as a great potential for large-scale heat pumps. For a CO2-neutral heat supply, the transition to large-scale heat pumps is indispensable. The reason why large-scale heat pumps have only been installed sporadically so far is that the price ratio of electricity to gas has been high until now. Therefore, people resorted to a heat supply via gas.

Despite the small number of units installed, the Technology Readiness Level (TLR) of large-scale heat pumps is 6 - 8, and even 9 for large industrial heat pumps.

Large-scale heat pumps are still largely manufactured as individual solutions and are therefore not as inexpensive to purchase as series products. Individual manufacturers offer their systems in a kind of modular system and can thus cover a heat output range of 350 – 3,100 kW. Large-scale heat pumps can cover temperature levels up to 130°C and achieve COPs of 4 to 7. [3]

2. Planning of energy concepts with large-scale heat pumps

The conceptual design is about the intelligent networking of electricity, heat and mobility in everyday life and the sensible integration of renewable energies into existing supply networks. One aspect of this is the use of existing heat sources on site, for example using waste heat from industry to provide heat to neighborhoods.

While smaller heat pumps with lower supply temperatures and low heating capacities have been established for many years in both residential and non-residential buildings, a supply concept with large-scale heat pump makes higher demands. Heat pumps suitable for these operating conditions are not yet standard products but are designed for the specific application. Frequently used air-to-water heat pumps, for example, must be able to raise the temperature of the ambient air to at least 80°C for a neighborhood supply (temperature level for the network if existing buildings are to be supplied and decentralized reheating or decentralized heat generators should not to be used) and may need to provide a thermal output of several megawatts, depending on the size of the heat network and the intended supply share of the heat pump. Many manufacturers of large-scale heat pumps have specialized in high performance and temperatures up to 90°C in the meantime and can offer models with good COPs.

2.1. Evaluation criteria

The conceptualization and elaboration of the supply system include the following points:

1. Demand assessment and load profiles

   For dimensioning the temperature of the supply network to e.g. neighborhoods, where the building-ages varies and usually several decades old, it is necessary to increase the flow temperature due to the associated heat losses.

   In order to consider the dimensioning of the components holistically, several potential expansion and connection stages of the supply network as well as the users must be taken into account. Therefore, variants must be considered with network expansion in the unrefurbished state of the houses and with reduced heating capacity in the refurbished state.

2. Simplicity and multifunctionality

   The biggest challenge in suppling existing neighborhoods is to provide heat at a temperature level where residents can decide today whether to replace their old oil or gas boiler with a local heating solution without having to immediately invest in insulation measures for their buildings. The concept should work both today and in several years, but in the long term the focus should be on reducing demand.

In terms of reducing complexity, the supply concept should be as simple as possible, while also maintaining a necessary degree of diversity and redundancy.

In order to implement the concepts, the individual systems, from heating systems to central storage facilities, must work together in a way that serves the system. For this purpose, the grids for heat, electricity and e.g. gas as a bivalent heat generator are intelligently connected to the individual systems in order to optimally use the mutual flexibility potentials.

3. Space requirements and suitability for an energy center

When determining a suitable location for the energy center - building or room in which all components for heat and power generation are placed, a basic requirement is that the location of the energy center be close to the key connection users and be accessible by transportation. In order to keep installation costs and distribution losses low, the distances between the heat storage facility, energy center and heating network should also be kept as short as possible.

In the conceptual design, attention must be paid to where large open spaces, which also offer space for redensification, are available in the area under consideration.

Furthermore, the location of the energy center must be compatible with the urban development plans. Conflicts of use must be avoided. A minimum distance from residential buildings must be maintained. The necessary redesignations in the land use plan to enable the construction of the heating center must be verified and clarified in advance.

The resulting space requirement of the energy center is determined by the size of the systems to be built, the dimensions (installation areas), the space requirement of the inspection areas and the maintenance of the distance to trees (treetops), neighboring buildings, neighboring properties, etc. In outdoor area, additional space must be provided for the transport infrastructure or the installation of the air-to-water heat pumps (incl. distance compliance). The area of the energy center is often largely determined by the air-to-water heat pumps.

When determining the space requirements, it should also be taken into account that the heating center can be expanded for future expansion scenarios of the network and the heat demand. Therefore, there should be potential for the energy center to be supplemented with additional components.

4. Time frame

An important criterion nowadays is the quick realizability of projects.

If the area is owned by the city/municipality or can alternatively be secured quickly, this is advantageous for the progress of the project. A critical path in the project is the preparation and amendment of development plans; in Germany, this should be planned for approximately 12 months. If an area is already earmarked for energy production in the development plan, this significantly increases the likelihood of implementation within the specified timeframe.

A longer time period of several years or even decades must be seen and planned, if the energetic refurbishment of the buildings have to be considered.

5. Noise protection

The heat generator, all supply components and especially air heat pumps can generate noise levels that may exceed the limits of residential areas. Therefore, noise barriers must be integrated into the installation concept. An evaluation of the noise emissions (sound calculator) is required in order to plan the necessary measures such as shielding wall / noise barrier or additional protection (cover damped 1.5 m depth).

A heat supply system or the implementation of a large-scale heat pump in a supply structure requires not only a suitable concept, but also good communication between different parties to achieve practical implementation. In addition to the points in above (section 2.1), the corresponding tasks should also include:

- approaching the main potential customers,
- educating local residents about the project.

Acceptance has a great influence on the achievement of the project's goals but it is difficult to assess regarding to the location of the energy center. An acceptance phenomenon is often described as "not in my backyard", i.e. general endorsement of a project as opposed to direct and personal influence. If the project is in an existing neighborhood, it is also complicated by the fact that almost every building has a different owner who has to be convinced of the project and can exert influence.

3. Project examples with large-scale heat pumps

Large-scale heat pumps have the potential to be used in many different ways. Due to their variability, they can cover large capacities as well as high temperatures (up to 130°C). In the following, projects will be presented, in which a large-scale heat pump is to be or has been integrated.

All projects presented are still in the planning stage, which is why only the initial planning results and calculations can be presented.

3.1. Project 1 – District in Heide

The first example shows the integration of heat pumps into a medium-sized district heating system currently planned for the city of Heide in northern Germany. The planned air/water heat pump should produce a supply temperature of at least 80°C and provide a thermal output of 1 to 2 MW_{th}. The project aims to design and implement a multimodal and sustainable energy supply system for the existing and future buildings in the district. (Fig. 1)

The selected district with an area of 20 ha is inhabited by approximately 500 people and features a diverse building structure. There are 108 single-family- and 47 multi-family-houses, as well as 27 non-residential buildings that are mostly businesses. Most of the buildings are heated with natural gas, some with oil and electricity. The annual energy demands of the existing buildings in the neighbourhood are approximately 1,683 MWh electricity, 4,932 MWh natural gas and 2,216 MWh oil, equivalent to a total of 3,410 t/a CO_2-emissions.

In the most ambitious planned stage for the district heating network, 125 buildings are connected. This includes 40 new buildings that are planned for the near future, resulting in a connection rate of 56%. Including the additional heat demand of the new buildings, the total heat demand provided by the heating grid adds up to 6,560 MWh/a.

In order to supply this heat and meet all the design criteria of the project, the energy supply system (Fig. 2) consists of various components:

- Photovoltaic installation spread over the roofs of the buildings in the district
- Dedicated electrical grid for collecting the PV electricity in the energy control central (required for regulatory reasons)
- Battery
- High temperature air/water heat pump (up to 90°C)
- Electrolysis (small, for research purposes)
- Combined heat and power plant (CHP), able to use natural gas and hydrogen
- Gas boiler used as back-up heater
- Thermal storage (water tank)
- District heating grid

An air/water heat pump is the primary heat generator, which is powered either by the photovoltaic, the output of a combined heat and power unit (CHP) or the public electricity grid. The latter is an important option for further CO_2-reductions, when electricity from the grid becomes less carbon intensive over time. Electricity can also be used to produce hydrogen in an electrolyser, which is installed for research and demonstration purposes. The use of hydrogen can be tested in the CHP in combination with natural gas, potentially used for hydrogen mobility or fed into the public gas grid. The electrolyser's waste heat can be used for heating, but only if the temperature is further increased. For this purpose, the waste heat can become a source for the heat pump. However, the available thermal power from the electrolyser is very small compared to the demand of the heat pump. Therefore, the ambient air remains the main source for the heat pump and the system is not dependent on the electrolysis, which makes the concept more easily transferable. The CHP is the secondary heat generator and, finally, a gas boiler is used as a back-up heater. The heat produced can be stored in a large water heat storage of about 500 m³ which can store heat for several days of use. A heating grid is used to transport the heat to the buildings.

Technically, the heat pump is the most challenging component. While smaller heat pumps with lower flow temperatures used in modern buildings have been established for many years, the presented concept has more demanding requirements. The buildings supplied are from different time periods and mostly several decades old. Supplying the heat via a heating grid with its inherent heat losses further raises the required flow temperature. Heat storage adds an additional requirement. The available thermal energy is defined by the usable temperature difference. To store the highest possible amount of heat in a given volume of water, a relatively high temperature with up to 90°C must be achieved. For those times when the storage alone is expected to meet the full demand of the grid, it can only do so while its outlet temperature surpasses the set temperature of the grid. The lower coefficients of performance resulting from the high supply temperature can be accepted if the heat pump is powered by local photovoltaic.

As a result, air/water heat pumps of this concept must raise the temperature of the heat source (environmental air) to 80 - 90°C, while providing thermal output power of 1 to 2 MW_{th}, depending on the final size of the heating grid and the targeted share of the heat pump (in relation to the CHP). Heat pumps suitable for these operating conditions are not yet of-the-shelf products, but instead designed for each use case. Due to the large temperature difference between source and load, manufacturers use a two stage process of either screw or piston compressors. The most common refrigerants are R717 (ammoniac) and R1234yf.

The air heat exchangers required to provide sufficient thermal source power need a large installation surface and create a noise level above the limits for residential areas of 60 dB(A) during day and 45 dB(A) at night. Therefore, noise protection barriers must be integrated into the installation concept.

Ground-source heat pumps using geothermal energy have been considered as an alternative, promising higher coefficients of performance and lower noise emissions. However, exploration drilling showed that the area available nearby for boreholes could provide only a fraction of the required annual energy demand, while increasing the investment costs drastically.

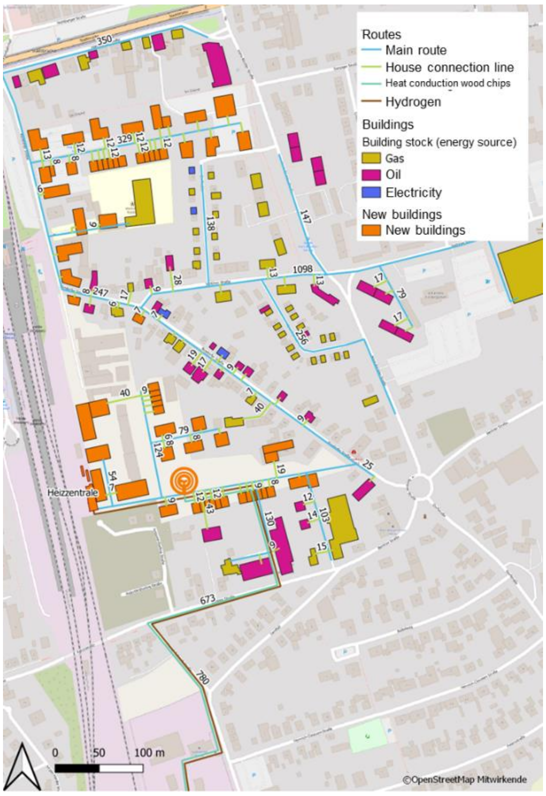


Fig. 1. Location plan project 1.

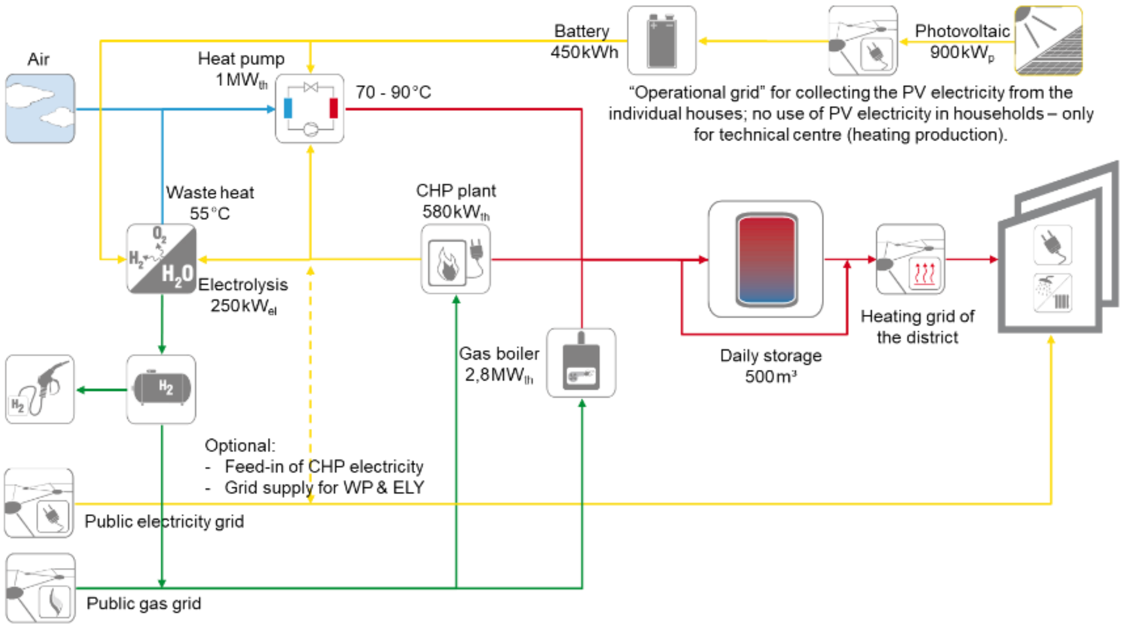


Fig. 2. Energy supply concept (below).

3.2. Project 2 – Building block in Kassel

Project 2 shows the implementation of a large-scale heat pump within a building block with around 150 residential units. The planned air/water heat pump must produce a supply temperature of at least 70 to 80°C and provide a thermal output of 640 kW. The aim of the project and the guiding principle of the building owner is the motto "away from gas"; all buildings in the building owner's portfolio are to be operated with renewable energy in the future. The project is still in the design phase; all boundary conditions are currently being defined and the energy consumption to date is being determined.

Fig. 3. Location plan project 2. [google maps]

3.3. Project 3 – District supply via four heating centers

Project 3 shows the implementation in four single small heating grids. The planned air/water heat pumps are to produce a supply temperature of at least 80 to 90°C and provide a thermal output of 7 MW in total (depending on the final size of the bivalent producer). The aim of the project is to convert four existing heating centers as a first step towards making all of the client's buildings and facilities fit for the future. The desire is to achieve climate neutrality for the properties.

In order to make all of the owner's sites sustainable in terms of construction and renovation activities as well as heat and power supply, the properties shown (Fig. 4) and the development potentials towards climate neutrality have to be assessed first. For the location examined, 90 buildings with about 550 residential units and a heated floor space of about 50,000 m² are assumed. The buildings accommodate different uses such as housing/assisted living or care facilities, workshop/warehouse, administration and social facilities.

Project 3 involves the conversion of four existing heating centers in the owner's entire property, which are currently operated via gas boilers and CHP units. The supply concepts to be developed should have a high share of renewable energy. The goal is to implement a share of 65 - 95% of the heat supply per heating center via air-water heat pumps (Fig. 5).

At present, the tasks are to examine the expandability of the respective heating system and the combination with thermal storage and photovoltaics for the use of self-produced electricity. The different building age classes and varying energy conditions of the buildings as well as the inhomogeneous structure at the site represent a challenge in the concept development and dimensioning. In addition, development scenarios for the site have to be worked out and defined with regard to future expansions and space requirements, as well as requirements for space- and use-specific needs.

The individual heating centers must cover a heat output of 485 kW to 5,145 kW and operate at a temperature level of 80/60°C or 90/70°C.

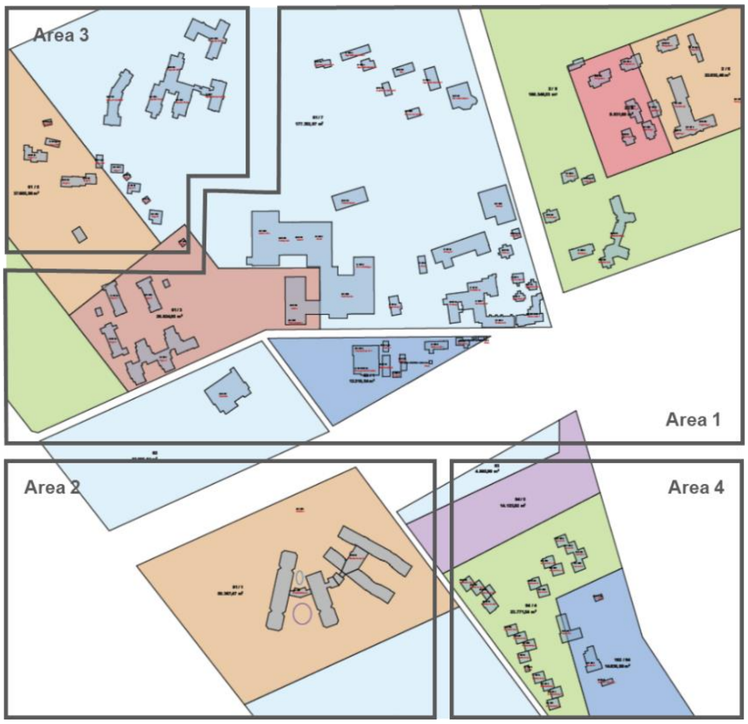


Fig. 4. Location plan project 3. [energydesign braunschweig GmbH]

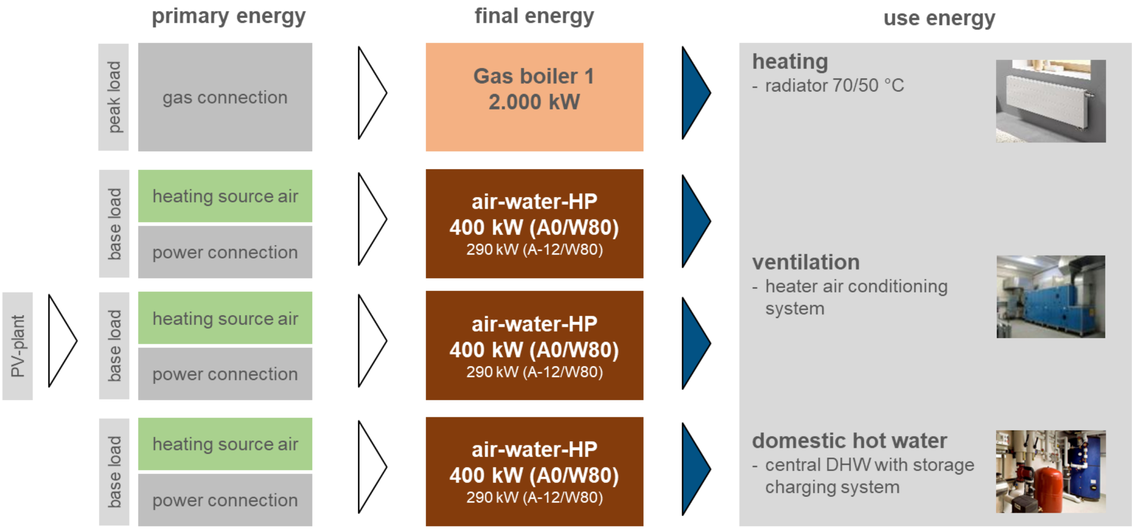


Fig. 5. Concept proposal for one heating center. [energydesign braunschweig GmbH]

The ecological assessment refers to the emissions that are emitted during the generation of heat via the current supply concept with gas boiler compared to the heat pump solution. The balance also includes the yields of the added PV systems and the electricity consumption. (see (1))

$$CO_2 emission = CO_2 emission\ factor\ x\ final\ energy\ (energy\ source) - CO_2 emission\ factor\ x\ electricity\ production\ PV\ plant \qquad (1)$$

Based on the examples of the new energy concepts with heat pumps for the heating centers in Area 1 and Area 3, there is an annual CO_2 saving potential of 53 and 78 % respectively compared to the current supply concept with gas boilers. This would mean a CO_2 reduction of around 515 to 1,210 tCO_2 annually.

- V1: heating center Area 1 – gas boiler
- V2: heating center Area 1 – Air to water heat pump
- V3: heating center Area 3 – gas boiler
- V4: heating center Area 3 – Air to water heat pump

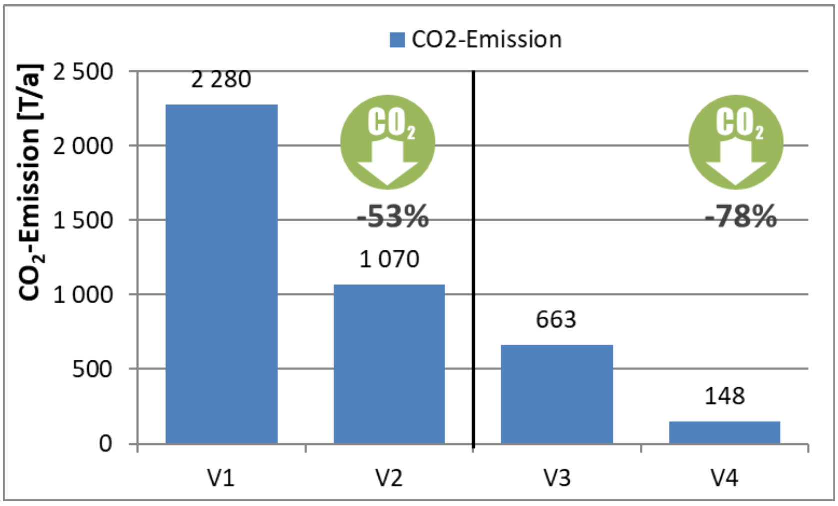


Fig. 6. CO_2-emission of the different variants of the heating center Area 1 + Area 3 (CO_2 emission factors: natural gas 270 g/kWh, electricity 400 g/kWh, displacement electricity -700 g/kWh) [energydesign braunschweig GmbH]

3.4. Projekt 4 – Data center concept study

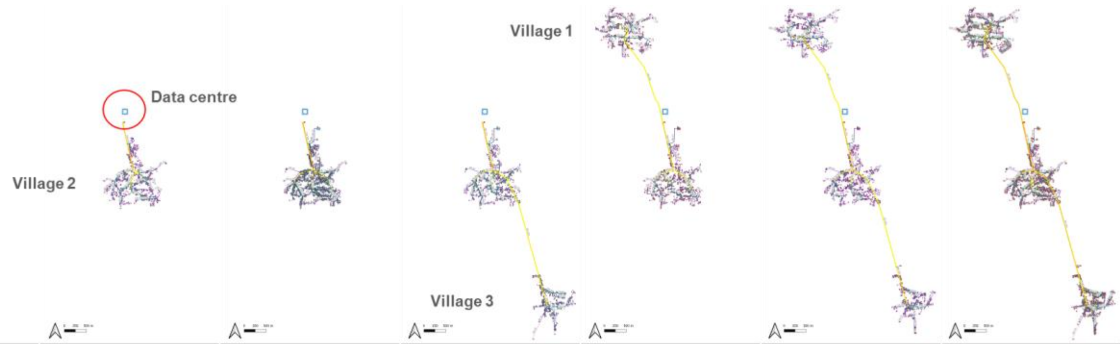
Project 4 shows the implementation of a large-scale heat pump with waste heat from a data center in a heating network. The planned water/water heat pump must produce a supply temperature of 80 to 90°C and provide a thermal output of 10 MW. The aim of the project is to use the waste heat from the data center under consideration, which has so far been released into the environment by conventional means via cooling fans, as a source for a new district heating network.

The data center is located between two rural villages with approx. 2,000 to 2,500 inhabitants each, which are currently mainly supplied with individual heating systems and fossil fuels. It is possible to implement waste heat recovery to supply the buildings via local heating networks. Other locations that could also be considered as heat consumers can be included. (Fig. 7)

In connection with the use of waste heat, a climate-neutral supply can be established for the surrounding villages in the building stock. The waste heat from the data center is available throughout the year at a temperature level of 20 - 36°C. (Fig. 8) Currently, a waste heat output of the data center (source) of 7 - 8 MW can be assumed (full expansion of the data center). With an annual performance factor for the heat pumps of 3.3, a theoretical 87,600 MWh/a of heat can be provided to the grid. This would even exceed the total heat demand of the expansion stages to supply the villages (Fig. 7).

Even if the data center could theoretically cover the total energy for the neighborhoods, it is assumed that the heat must be stored - need for a large heat storage tank - and that additional heat generators must be integrated. The following variants are still considered in the study as additional heat generators and heat grid feeders:

- Variant A: Heat pump + electrode boiler (as back-up heating)
- Variant B: Heat pump + electrode boiler + CHP (electricity energy system)
- Variant C: Heat pump + electrode boiler + CHP (electricity energy system) + heat pump for storage (to extract heat from the storage above a certain temperature level)
- Variant D: Heat pump + high voltage electrode boiler [4] + CHP (electricity-fired power plant) + heat pump for storage + wind turbines
- Variant E: Heat pump + electrode boiler (as back-up heating) + wind turbines
- Variant F: Heat pump + electrode boiler + CHP (straw-fired energy plant) + wind turbines



	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
	Village 2	Village 2	Village 2 + 3	Village 1 + 2	Village 1 - 3	Village 1 - 3
Connection to the grid	60%	100%	60%	60%	60%	100%
Inhabitants	1,455	2,432	2,076	2,569	3,183	5,300
Buildings	482	804	735	847	1,099	1,833
Total heating demand	16.2 GWh	28.5 GWh	25.7 GWh	28.8 GWh	37.0 GWh	62.5 GWh
Total heating capacity	5.8 MW	10.0 MW	9.1 MW	10.3 MW	12.4 MW	20.1 MW
Route length	14.0 km	16.0 km	22.8 km	27.1 km	35.5 km	39.2 km

Fig. 7. Location plan and Expansion scenarios for the heating supply grid.

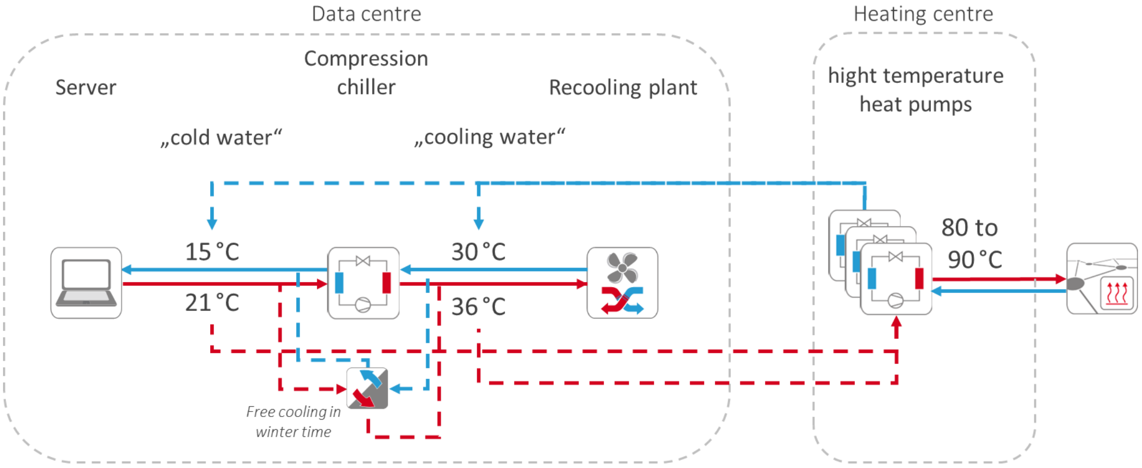


Fig. 8. Supply concept of the heating grid with integration of the data center as a heating source

The ecological assessment refers to the emissions (see (1)) that are emitted during the generation of heat via the current supply concept using decentralized gas boilers (in Fig 9 the reference) compared to the neighborhood supply with heat pumps (in Fig. 9 Variant A, B, E and F). The balance also includes the yields of the wind turbines.

The concept variants were worked out using level 3 as an example. The results show an enormous ecological savings potential. An annual CO_2 saving potential of about 45 - 97 % (depending on the wind power implementation) compared to the current supply concept is available. This would mean a CO_2 reduction of around 3,185 to 7,122 tCO_2 annually.

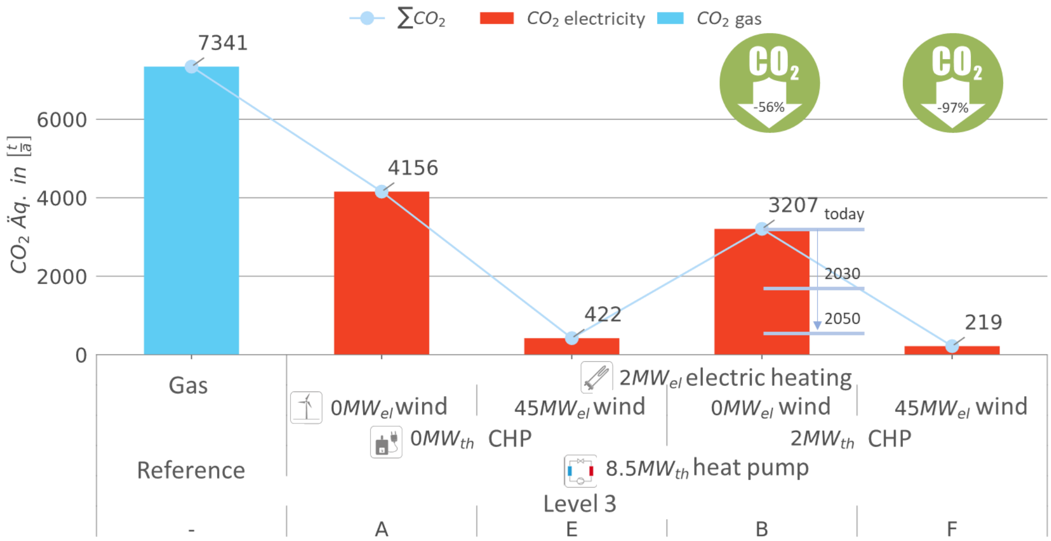


Fig. 9. CO_2 emissions of the different variants for heat generation (CO_2 emission factors: natural gas 250 g/kWh, grid electricity 401 g/kWh)

3.5. Projekt 5 – research center for hydrogen technology

Another example is the integration of a large-scale heat pump in a hydrogen technology research facility. The project aims to improve the overall efficiency of the electrolysis by decoupling the waste heat and using it for heating applications. For this purpose, different heat exchangers are to be implemented in combination with a heat pump.

4. Conclusion

Germany is to become greenhouse gas neutral by 2045, to reach this the 65% renewable energy target for heat generation has been introduced. However, this target can only be achieved if the heat supply is restructured in terms of energy and can do without fossil fuels. Large-scale heat pumps will therefore play an important role in the medium and long-term transformation of the heat supply.

In newly built residential buildings (single-family and multi-family buildings) and non-residential buildings (office buildings), the heat pump has already become the standard heating appliance. However, the situation is different in the commercial sector, in existing buildings and at the neighborhood level. Here, the heat pump is still too rarely seen as the ideal technology. The examples given show that this should no longer be a problem in the future at the neighborhood and commercial level, and that municipalities, project developers, public utilities and other energy suppliers in particular see the opportunity to massively advance climate protection when building or modernizing neighborhoods and building blocks - and, quite incidentally, to establish sustainable business models with long-term customer relationships. An individual solution can now be found for every large property/project thanks to the very diverse use of large-scale heat pumps.

However, in order to be able to exploit the potential of this energy supply variant in the best possible way, the design and dimensioning as well as the integration into the overall supply concept are relevant. At present, unfortunately, the large-scale heat pump is still a special design that has to be planned according to the specific application.

The planning and dimensioning of supply concepts with large-scale heat pumps includes in advance an inventory to present the basics and objectives of the concept. In the first step, the demand and load profiles must be determined. If the project involves existing systems / existing buildings, future renovations and changes to the buildings must be taken into account. But also necessary changes to the existing concept, like the adjustment of the supply temperatures, have to be considered. Existing systems require increased attention during replanning so that all individual systems, from the heating system to the central storage tank, are coordinated and work together in the future.

Other factors, albeit secondary locations, should not be neglected. For example, the new location of the energy center, if required, or in general the space requirements of the new supply system must be examined and defined. Existing technical rooms could become too small if additional components such as storage tanks or the heat pump itself have to be installed.

In the entire planning process, attention must be paid to early coordination and clarification of goals and target values, as well as communication with all stakeholders and their involvement in the processing and concept development.

The projects shown relate primarily to the replacement and exchange of gas boilers and the implementation of large-scale heat pumps in the existing supply. The supply concepts are increasingly changing from a decentralized to a centralized supply. All concepts have the goal of saving as much CO_2 as possible in order to meet climate protection targets. It can be clearly seen that just by exchanging the old heat generators (fossil fuels, gas) to a heat pump (regenerative energy source) the CO_2 emissions can be reduced more than 50%. Furthermore, a high share of the heat supply should be covered by the heat pump and thus renewable. Depending on the concept, “>50% “up to 100% (total exchange) can be achieved as coverage share.

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