The roll-out of large-scale heat pumps in Germany

Strategies for the market ramp-up in district heating and industry

STUDY

Agora Energiewende

Fraunhofer IEG

The roll-out of large-scale heat pumps in Germany

PUBLICATION DETAILS

STUDY

The roll-out of large-scale heat pumps in Germany. Strategies for the market ramp-up in district heating and industry.

COMMISSIONED BY

Agora Energiewende
Anna-Louisa-Karsch-Straße 2
10178 Berlin | Germany
Phone: +49 (0)30 700 14 35-000
www.agora-energiewende.org
info@agora-energiewende.de

PROJECT PARTNERS

Fraunhofer-Einrichtung für Energieinfrastrukturen und Geothermie IEG
Gulbener Straße 23 | 03046 Cottbus
https://www.ieg.fraunhofer.de/

Project management Fraunhofer IEG:

Björn Drechsler
bjoern.drechsler@ieg.fraunhofer.de
Fabian Ahrendts
fabian.ahrendts@ieg.fraunhofer.de

Translation: Ray Cunningham
Typesetting: Kamila Humienna
Title picture: Dusan Petkovic | Shutterstock

316/03-S-2023/EN
Version: 1.0, December 2023

PROJECT MANAGEMENT

Uta Weiß
uta.weiß@agora-energiewende.de
Anna Kraus
anna.kraus@agora-energiewende.de

AUTHORS

Fabian Ahrendts, Björn Drechsler, Julian Hendricks, Jan Küpper, Susanne Lang, Tim Peil, Daniel Scholz, Elena Timofeeva, Matthias Utri, Lisa Weidinger (all Fraunhofer IEG); Anna Kraus, Uta Weiß, Simon Müller (all Agora Energiewende).

The responsibility for the contents of Chapters 2 to 8 lies exclusively with Fraunhofer IEG. Agora Energiewende produced the summary (Chapter 1). The recommendations for action (Chapter 9) were co-authored by Fraunhofer IEG and Agora Energiewende.

This publication is available for download as a PDF under this scan code.

Please cite as:
Agora Energiewende, Fraunhofer IEG (2023): The roll-out of large-scale heat pumps in Germany. Strategies for the market ramp-up in district heating and industry.

www.agora-energiewende.org

ACKNOWLEDGEMENTS

This study was only possible thanks to the commitment of many other colleagues. For their tireless support, we would like to thank Nikola Bock, Chrissie Donnelly, Janne Görlach, Alexandra Langenheld, Maxi Matzanke, Julia Metz, Jahel Mielke, Paul Münnich, Lea Marie Nesselhauf, Frank Peter, Ada Rühring, Barbara Saerbeck, Hendrik Staudinger, Alexandra Steinhardt, Gloria Watzinger, Anja Werner (all Agora Energiewende).

Preface

Dear reader,

This study on large-scale heat pumps provides an overview of the current market status and the potential of large-scale heat pumps and their use in district heating and looks at the political priorities for action required for their deployment.

The roll-out of large-scale heat pumps requires a triad consisting of strategic goals and incentives from the public authorities, technological innovation on the part of manufacturers and accelerated implementation by district heating providers and industry. This entails a solution-oriented partnership between private companies and the public sector. Against this background, it makes sense to use the idea of the *Mission Economy*, as put forward by the Italian American economist Marianna Mazzucato, as a way to promote the market ramp-up of large-scale heat pumps for the German climate transformation.

This new approach to solving major societal tasks is characterised by an active partnership between the private and public sectors in which the state defines the challenges and problems to be solved without imposing detailed prescriptions and provides investment confidence and security for the private sector. In return, private actors commit to goals such as cost reductions or attractive products and services for customers. In addition, the state takes on entrepreneurial risks, but also takes a share of the returns.

With this study, we want to make a contribution to exploiting the considerable potential of large-scale heat pumps and district heating systems for a successful heat transition.

I hope you enjoy reading it!

Simon Müller
Director Germany, Agora Energiewende

Findings at a glance:

1. **Heating applications in the range up to 200 degrees are responsible for over three quarters of Germany's fossil gas consumption and over a quarter of its greenhouse gas emissions.** Currently, fossil fuels dominate the heat supply in industrial processes, buildings and district heating systems. In order to achieve the climate targets and reduce fossil gas consumption, it is therefore crucial to switch to climate-neutral options based on renewable energy sources.

2. **The entire heat demand in Germany up to 200 degrees can technically be covered by heat pumps.** As part of this, large-scale heat pumps can exploit considerable potentials offered by geothermal energy, water bodies and waste heat. By 2045, large-scale heat pumps could provide 70 percent of the district heating supply and thus replace a very large proportion of the fossil gas used.

3. **Large-scale heat pumps are a proven technology that has considerable market potential in Germany.** However, there were only 60 megawatts of installed capacity in Germany in 2023. Complex planning and approval procedures are slowing down the market ramp-up. In addition, the existing financial support system under the Combined Heat and Power Act (KWKG) and the higher tax burden on electricity compared to fossil gas have so far favoured gas-based heating options – these perverse incentives must be eliminated.

4. **A rapid ramp-up of large-scale heat pumps requires a cleverly coordinated mix of instruments.** Of overriding importance is a clear overall goal, combined with energy prices that are in line with the transformation and a reform of the network use charges. Manufacturers should use the resulting planning certainty to drive innovation and reduce manufacturing costs. A revised framework of financial support and measures to speed up large-scale heat pump projects in district heating systems can then stimulate demand.

Contents

List of figures and tables

List of acronyms

AGFW	Arbeitsgemeinschaft Fernwärme (Der Energieeffizienzverband für Wärme, Kälte und KWK e. V.) (Working Group District Heating (Energy Efficiency Association for Heating, Cooling and CHP))
ArbStättV	Arbeitsstättenverordnung (Workplaces Ordinance)
BEW	Bundesförderung für effiziente Wärmenetze (Federal funding for efficient district heating systems)
BauGB	Baugesetzbuch (Building code)
BEHG	Brennstoffemissionshandelsgesetz (Fuel Emissions Trading Act)
BetrSichV	Betriebssicherheitsverordnung (Industrial Safety Regulation)
BMBF	Bundesministerium für Bildung und Forschung (Federal Ministry of Education and Research)
BImSchG	Bundes-Immissionsschutzgesetz (Federal Immission Protection Act)
BMWK	Bundesministerium für Wirtschaft und Klimaschutz (Federal Ministry for Economics and Climate Action)
BWP	Bundesverband Wärmepumpe e. V. (Federal Heat Pumps Association)
CAPEX	Capital expenditures
COP	Coefficient of performance
dena	Deutsche Energie-Agentur GmbH (German Energy Agency)
EEG	Gesetz für den Ausbau Erneuerbarer Energien (Erneuerbare-Energien-Gesetz) (Act for the Expansion of Renewable Energies)
EnEfG	Energieeffizienzgesetz (Energy Efficiency Act)
EPC	Engineering, procurement and construction
FCKW	Fluorchlorkohlenwasserstoffe (Chlorofluorocarbons)
GEG	Gebäudeenergiegesetz (Buildings Energy Act)
GW/GWh	Gigawatts/Gigawatt hours
GWP	Global warming potential
HFC	Hydrofluorocarbons
HFO	Hydrofluoroolefin refrigerant
HOAI	Honorarordnung für Architekten und Ingenieure (Fee schedule for architects and engineers)
HTWP	Hochtemperatur-Wärmepumpe (High temperature heat pump)
IEA	International Energy Agency
IHX	Internal heat exchanger
KSG	Bundes-Klimaschutzgesetz (Federal Climate Protection Act)
kW/kWh	Kilowatts/Kilowatt hours
KWK	Kraft-Wärme-Kopplung (Combined heat and power, CHP)
KWKG	Gesetz für die Erhaltung, die Modernisierung und den Ausbau der Kraft-Wärme-Kopplung (Act for the preservation, modernisation and expansion of combined heat and power generation, CHP Act)
KWW	Kompetenzzentrum Kommunale Wärmewende (Competence centre for the municipal heat transition)
LNG	Liquid natural gas
LULUCF	Land use, land-use change and forestry
LWG	Landeswassergesetze (State Water Acts)
MVR	Mechanical vapour recompression
MW/MWh	Megawatts/Megawatt hours
Mt	Megatonnes
ODP	Ozone depletion potential
OPEX	Operational expenditures
PFAS	Per- and polyfluoroalkyl substances
PKNS	Plattform Klimaneutrales Stromsystem (Climate-Neutral Electricity System Platform)
PPA	Power purchase agreement
PtG/PtL	Power to Gas / Power to Liquid
TCP	Technology collaboration programmes
TRL	Technology readiness level
TWh	Terrawatt hours
UVPG	Gesetz über die Umweltverträglichkeitsprüfung (Environmental Impact Assessment Act)
Vbh	Vollbenutzungsstunden (Full load hours, flh)
WHG	Wasserhaushaltsgesetz (Water Resources Act)

1 Summary

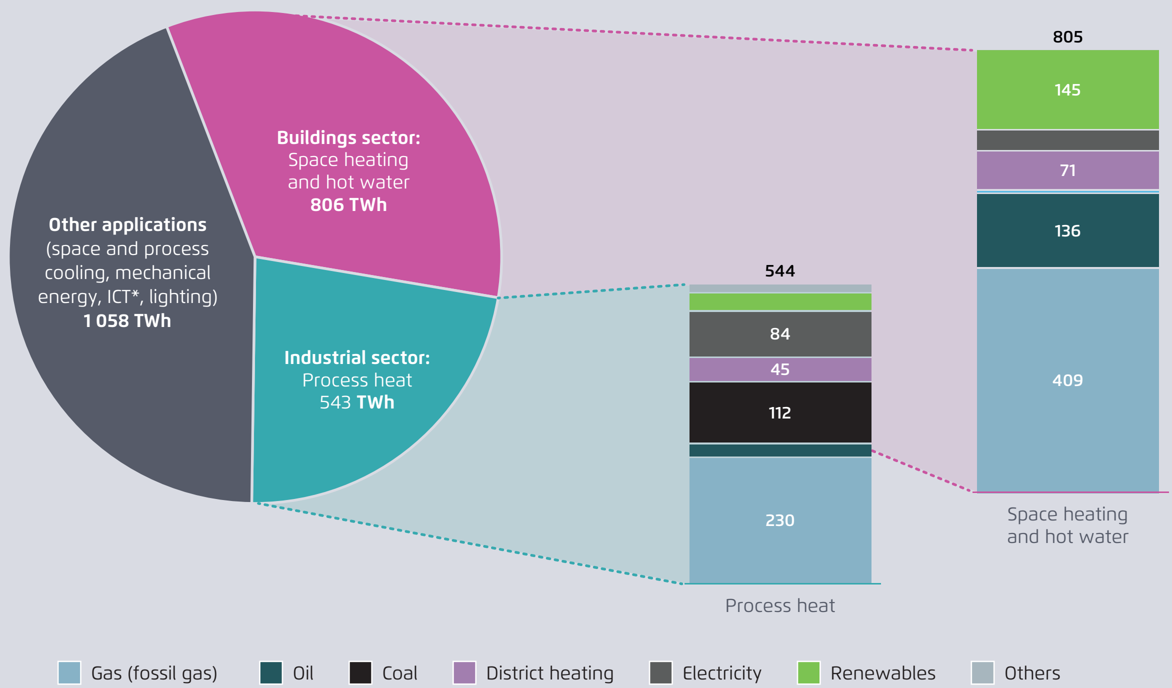
Background

A climate-neutral heat supply is crucial to Germany meeting its climate targets. Germany has set itself the binding target of being climate-neutral by 2045. A key milestone on that path is the equally binding target of -65 percent greenhouse gas emissions by 2030 compared to 1990. The heating sector plays a key role in reaching the climate targets: almost 80 percent of the heat demand in buildings and industry is still met by burning fossil fuels.

The majority of the heat demand is for low temperature ranges. The supply of space and process heat up to 200 °C and of hot water requires considerable energy and fossil gas input and produces high CO_2 emissions. These temperature ranges fully encompass the temperature range (generally 90 °C to 110 °C) required in district heating systems, as well as at least one third of the industrial heat demand (UBA 2017). Heat demand up to 200 °C was responsible for 43 percent of Germany's final energy consumption in 2021; it involved fossil gas consumption of 494 terawatt hours (TWh) (76 percent of total consumption); and it caused greenhouse gas emissions of 215 million t CO_2-eq.

Final energy consumption by application in Germany 2021 (left)
Energy sources of supply (right)

Figure A



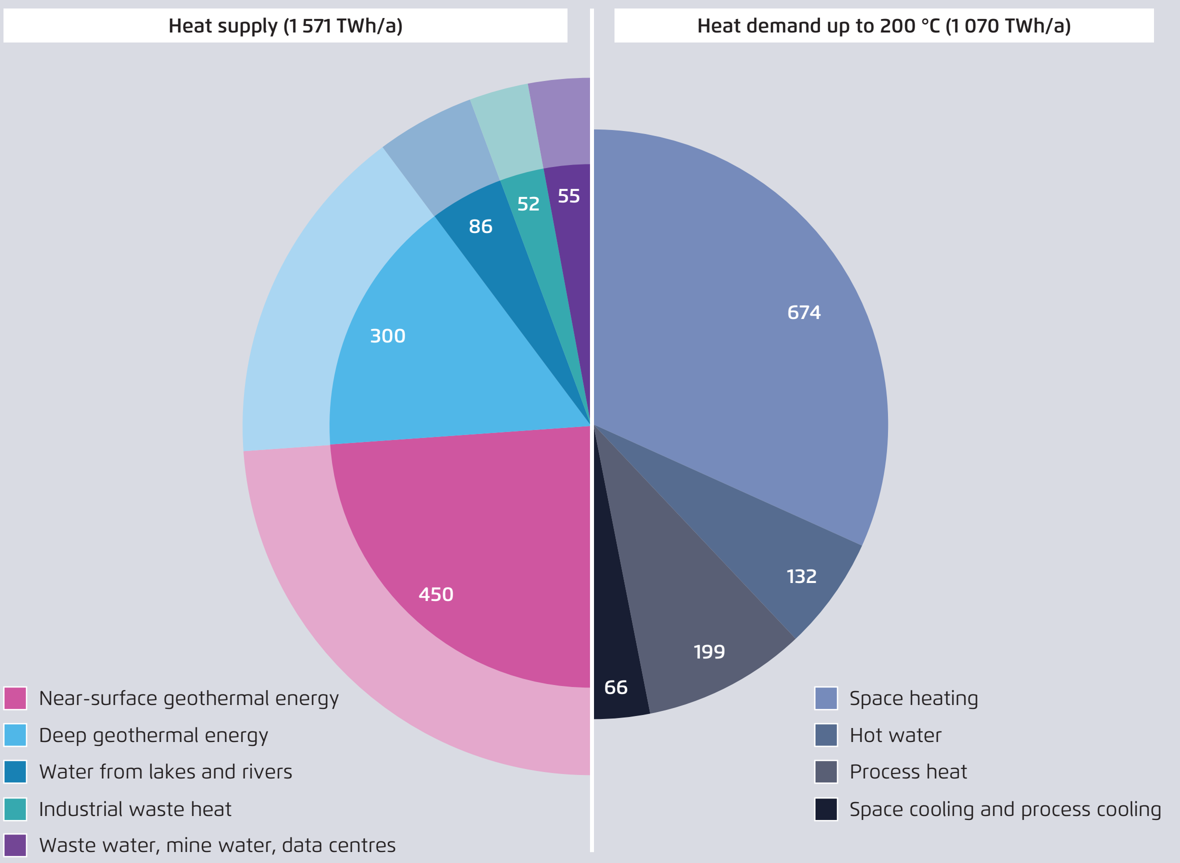
Agora Energiewende based on AGEB (2022b). * Information and communication technology

Potential, state of the market and main areas of innovation

Large-scale heat pumps are a key technology for the climate-neutral operation of district heating systems and supply of industrial process heat up to 200 °C. Heat pumps enhance natural heat sources by using electricity to raise them to a higher temperature level and thus make them more usable. The amount of electricity required for this is only a fraction of the heat generated; in other words, the efficiency is significantly higher than 100 percent. The smaller the required temperature lift[1], the greater the efficiency advantage. Even today, target temperatures of up to 200 °C can be achieved efficiently. For the purposes of this study, all heat pumps with a

1 The temperature lift is the difference between the temperature of the heat source used (e.g. air, ground, river water or a sewage treatment plant) and the flow temperature generated in the heat pump, which supplies heat to a heating network or an industrial process, for example.

Comparison of the potential heat supply* via heat pumps and the heat demand up to 200 °C** in Germany (excluding ambient air) — Figure B



Fraunhofer IEG based on Born et al. (2022), Bracke et al. (2022), Kammer (2018), Gerhardt et al. (2019), Fritz und Pehnt (2018), Wolf (2017), Stobbe et al. (2015). * The heat supply is made up of the potential supply from different heat sources (darker colours) plus the necessary operating power (lighter colours) for the heat pumps, assuming an average COP of 2.5. ** Heat demand based on final energy consumption in Germany in 2021, excluding process heat of private households and process heat > 200 °C.

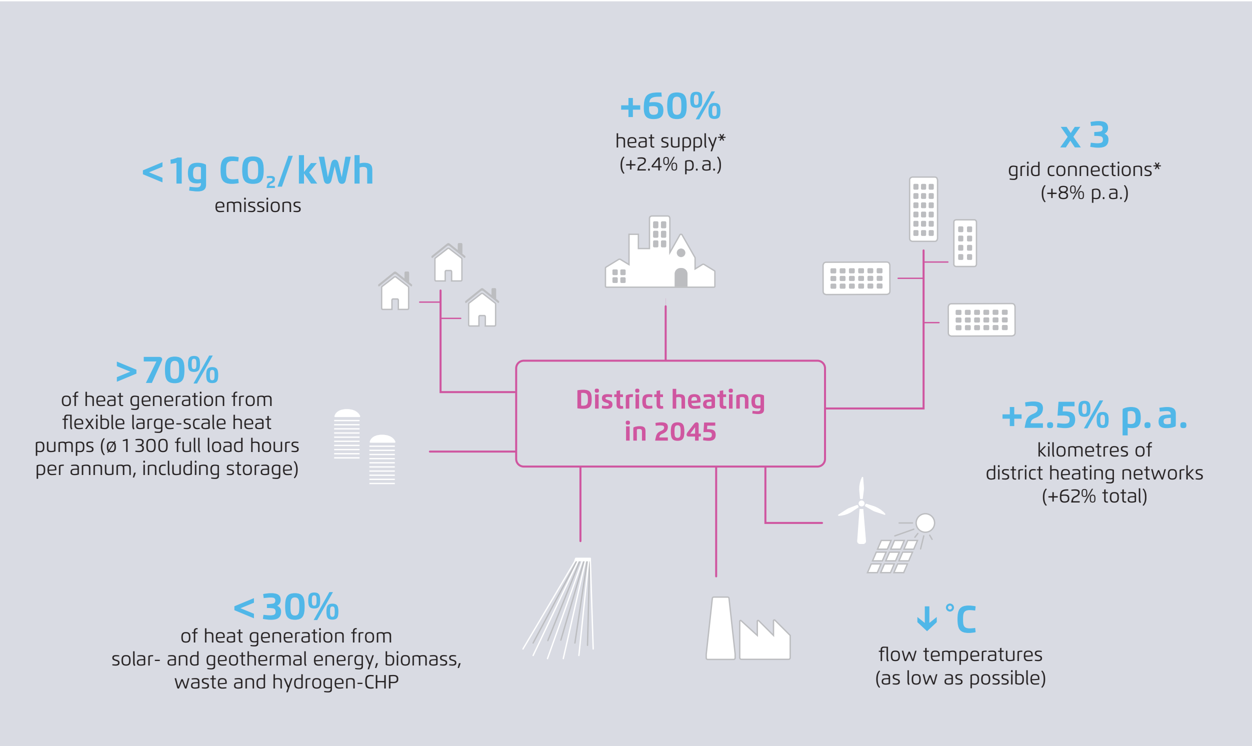
thermal output of 500 kilowatts (kW) or more are defined as large-scale heat pumps.

Over the long term, the demand for heat up to 200 °C in Germany can be met by heat pumps. Excluding air as a heat source, near- surface and deep geothermal energy have by far the greatest potential, followed by lakes and rivers, industrial waste heat, wastewater, disused coal mines and data centres (Figure B).

Large-scale heat pumps could provide over 70 percent of district heating in 2045. District heating systems are a prerequisite for a climate-neutral buildings stock in 2045 – and large-scale heat pumps are the key. However, heat generation for district heating systems is facing fundamental changes, because currently the majority of district heating is still provided by fossil-fuelled combined heat and power plants (CHP plants). In the future, this fossil heat can be replaced primarily by large-scale heat pumps – this requires an average annual expansion of at least 4 gigawatts (GW) of new thermal large-scale heat pump capacity up to 2045. This also means that the key technology for the climate-neutrality of district heating systems is already known today, is at a stage of technological maturity and can bring about significant CO_2 savings if the necessary expansion takes place before 2030.

In industry, accelerating the ramp-up of heat pumps can reduce gas consumption by 25 percent by 2030 compared to 2021. Huge potential has been identified above all in the chemical, paper and food industries as well as in mechanical engineering, for example in drying processes or steam generation. Large-scale heat pumps are

The typical district heating system of a German city in 2045* — Figure C



Fraunhofer IEG based on Fraunhofer ISI et al. (2022); * compared to 2020; numbers based on the long-term scenarios III (Fraunhofer ISI et al. 2022b).

an efficient way to generate climate-neutral heat for industry. They can not only supply high temperatures based on environmental heat, but through the intelligent use of waste heat they can also be used at temperatures even above 200 °C (Agora Industry and FutureCamp 2022).

Large-scale heat pumps use proven technologies and can be scaled up quickly. The market for large-scale heat pumps in Germany, however, is still in its infancy. For the temperature range required for district heating systems, manufacturers already have a wide range of market-ready large-scale heat pumps on offer. Many of them are already operating reliably in a number of European countries. In Germany, by contrast, only a few large-scale heat pumps have been installed so far in both the district heating and industrial sectors. A medium double-digit number of systems amounting to a total installed heating capacity of less than 100 megawatts (MW) are currently installed, and another 600 MW are either under construction or in the planning stage.

A systematic market ramp-up can promote technical innovation and cost reductions. There is considerable potential for innovation,

Maximum flow temperatures and heating capacities of available large-scale heat pumps — Figure D

Fraunhofer IEG (2023) based on Figure 42 in Appendix A.3

for example in compressors – the key component of heat pumps – with regard to new refrigerants, more flexible modes of operation and higher target temperatures. In addition, large-scale heat pumps in the future must be designed in such a way that their operation can be flexibly adjusted to the prevailing situation on the electricity market.

The availability of standardised options in the range from 1 MW to 10 MW is crucial for a successful ramp-up. Currently, the market segment above 1 MW capacity is still strongly characterised by customised solutions and very low production volumes. Manufacturers assume that there is still considerable potential for more standardisation in the range up to approx. 10 MW heat output. Since heat pumps offer considerable economies of scale, the availability of larger standard components contributes significantly to cost reductions and can at the same time simplify project planning. It should therefore be a focus for the market ramp-up.

Recommendations for action

Until 2045, on average, well over 300 individual projects with a new large-scale heat pump capacity of more than 4 GW as well as 800 km of new heating pipelines will have to be planned, financed and constructed every year. This is a challenge for the whole society, one that requires clear prioritisation from politicians and a high level of innovation and efficiency from manufacturers and district heating operators. It is crucial that a cleverly timed combination of price signals, support measures and regulatory requirements enables a rapid ramp-up, while at the same time allowing supply chains and implementation capacities to grow without problematic bottlenecks.

The measures required can be categorised into three core areas for action. First, a coherent overall framework is required that combines a clear strategic vision with consistent price signals for the use of energy carriers and infrastructures. Secondly, the potential for innovation, scaling and cost reduction must be exploited consistently and quickly by manufacturers. Thirdly, the transformation of district heating systems must also be accelerated on a structural level through a reform of the support framework and a package of measures to simplify its implementation.

Overall framework: clear targets, efficient energy prices and revised network use charges

The potential offered by large-scale heat pumps and district heating systems for a climate-neutral energy supply can only be exploited quickly and fully if manufacturers and users can rely on the ramp-up trajectory and if market forces support the ramp-up through efficient price signals. In addition to a clearly articulated, credible overall vision for the ramp-up path, the most important instruments are the relative prices of different energy sources and the user charges for infrastructures.

- → In order to create clear targets for manufacturers and operators, a stakeholder process at federal level (a large-scale heat pump summit) should establish a long-term overall goal with ambitious interim targets.
- → The economic viability of large-scale heat pumps in planning and operation depends crucially on the **ratio of electricity to gas prices** – currently, taxes, levies and charges are creating perverse incentives. The new emissions trading system (ETS2) planned at the European level for the buildings and transport sectors and/or an increase in prices in the Fuel Emissions Trading Act (Brennstoffemissionshandelsgesetz, BEHG) can correct the current distortion. Furthermore, electricity continues to be subject to higher taxes, levies and surcharges than gas. A further reduction of these perverse incentives, for example through a reduction of the electricity tax to the European minimum level, can help to remedy this situation.

→ The introduction of **time-variable grid charges** is essential to ensuring that heat pumps use renewable electricity in a way that supports the system and does not overburden the grid.

Large-scale heat pumps: rapid cost reduction, further performance enhancements and increased production capacities

Large-scale heat pumps have considerable potential for performance enhancements and simultaneous cost reductions – manufacturers must consistently exploit this potential and should be strategically supported in doing so. The basic technical principle and the individual components of heat pumps have been known and commercially available for decades. However, the industrial mass production of efficient large-scale heat pumps is still in its infancy due to a lack of demand. An anticipatory expansion of supply is therefore essential to avoid supply bottlenecks or sharp cost increases when demand picks up quickly.

→ **An expansion of standard technical systems to thermal output ranges of up to 10 MW should be prioritised.** Firstly, the unit investment costs (euros per MW) can be reduced through the use of bigger plants. Secondly, standardisation makes higher unit numbers possible and thus economies of scale in production. For the market ramp-up, a focus on enabling a large number of projects in this medium output range can be particularly beneficial.

→ **Further developments in compressor technology offer considerable potential for improving the performance of large-scale heat pumps and for the use of natural refrigerants.** Technical innovations in compressors and refrigerants enable performance improvements with respect to three core characteristics. Firstly, higher target temperatures and temperature lifts can be achieved. Secondly, efficiency increases are possible, i.e. an improvement in the COP. Thirdly, greater flexibility can be achieved by enabling operation across a wider output range and with faster load changes and start-up and shutdown sequences. This facilitates a system-supporting mode of operation.

→ **Building up industrial manufacturing capacity should be a focus of industrial policy.** Only with a significant expansion of global and European manufacturing capacity can the potential of large-scale heat pumps be fully exploited. In the context of a stronger emphasis on resilient supply chains, the development of European manufacturing capacities also has a central role to play – so the establishment of new production facilities, combined with instruments promoting long-term security of demand, should be prioritised.

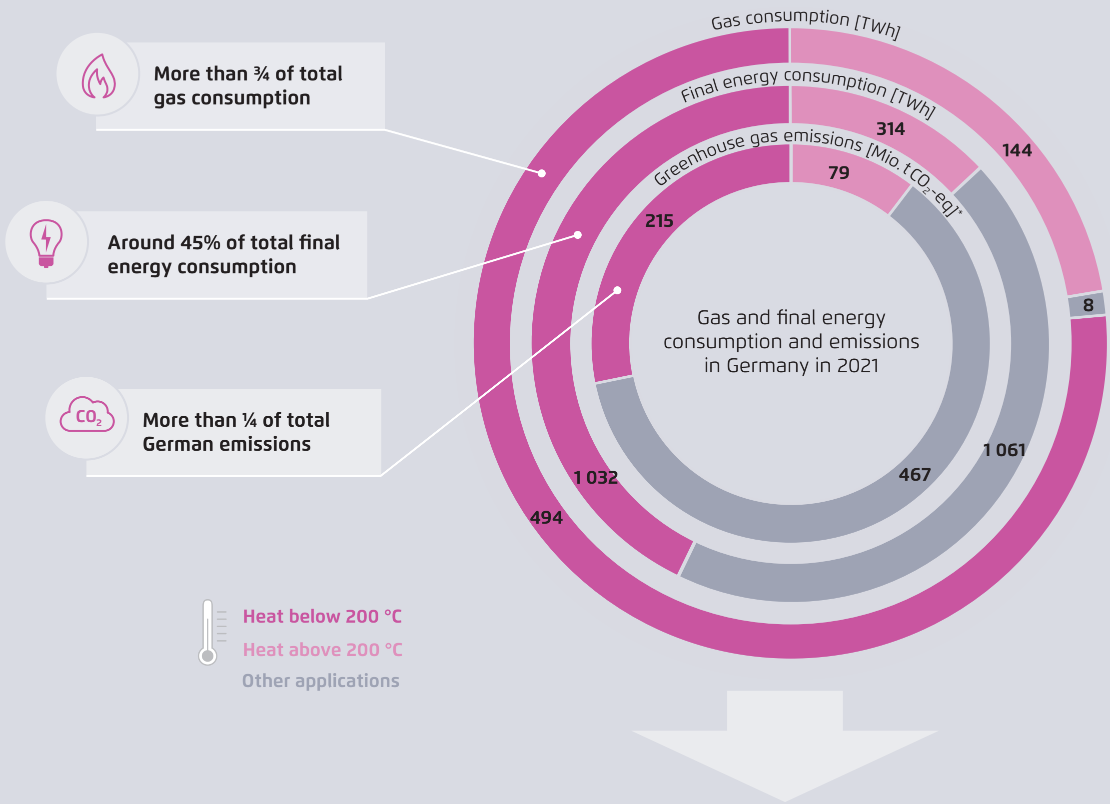
District heating systems: a streamlined funding landscape, mandatory planning and simplified implementation

The extension and new construction of district heating systems, along with their upgrading, are key drivers for the market ramp-up of large-scale heat pumps – such measures must therefore be simple, quick and economically attractive to carry out. In order to achieve this goal, adjustments are necessary in three areas. Firstly, financial support systems must be improved or better coordinated. In particular, the existence of parallel subsidy schemes under the long-standing Combined Heat and Power Act (Kraft-Wärme-Kopplungs-Gesetz, KWKG) and the new federal subsidy for efficient district heating systems (Bundesförderung Effiziente Wärmenetze, BEW) currently leads to perverse incentives. Secondly, a local energy distribution strategy must be developed: based on a binding municipal heating plan, it will identify the areas where a network-connected heat supply should be installed as a priority. Thirdly, the time required for projects to be completed must be halved from currently up to six years to around three years by a package of modifications and simplifications to approval and implementation processes.

- **Alongside the BEW Guideline, the old support system for CHP continues to exist under the CHP Act.** This currently leads to significant perverse incentives, in particular to designs for heat pumps that are too small and to the continuous heat-led operation of CHP plants and heat pumps, which is highly problematic for the electricity system as a whole. This should be corrected via a fundamental reform of the CHP Act.
- **The financial resources of the BEW must be increased.** The financial resources of 3 billion euros provided for in the programme are by no means sufficient to support the market ramp-up as outlined in this study. Against this background, an analysis by Agora Energiewende (Agora Energiewende, 2022) recommended increasing the funding by a further 8 billion euros to a total of 11 billion euros.
- **Municipal heat planning must be introduced on a mandatory basis and further developed into a local energy distribution strategy.** The success of the heat transition depends on its implementation on the ground – and for this, nationwide municipal heat planning is crucial. Binding regulations must be established at the federal level so that reliable and comparable heat plans are created in all local authorities. In addition, municipal heat planning should be further developed into a local energy distribution strategy that enables the coordinated planning and construction of electricity, gas, hydrogen and district heating networks.
- **Accelerated planning for large-scale heat pump projects, simplified approval procedures and enhanced implementation capacities are crucial.** Shortening the time required for projects from the current four to six years to around three years requires a bundle of individual measures each of which can only make a limited contribution on its own, but which have a strong impact as part of an overall package. These are presented in detail in Chapter 8.

The recommendations for action made in this study represent a coherent and comprehensive overall package that can help the ambitious ramp-up of large-scale heat pumps and district heating systems to succeed. It is clear that further analyses and more precise information are needed in many areas. However, the study underlines the contribution that innovative approaches in heat supply can make to a successful transition to climate neutrality – provided they are put into action quickly and ambitiously.

Heat up to 200 °C: potential for reducing emissions, gas and final energy consumption — Figure E



Priorities for action for climate-neutral heat up to 200 °C

Framework conditions: clear targets, efficient energy prices and reformed network use charges	Stakeholder process for clear vision (large-scale heat pump summit)
	Profitability of electricity price versus gas price; CO_2-pricing
	Reformed grid tariffs supporting flexibility in the energy system and faster grid connections
Large-scale heat pumps: fast cost reduction, further improvements in performance, increased production capacities	Standardisation, modularisation, and economies of scale for products and processes
	Key areas of innovation: higher temperature ranges, improved efficiency, flexible operation, wider use of natural refrigerants
	Increase in production capacities
District heating: streamlined subsidy schemes, mandatory heat planning, simplified implementation for large-scale heat pump projects	Increase in subsidies and removal of perverse incentives
	Mandatory municipal heat planning, later to be expanded into a municipal energy distribution strategy
	Faster and easier planning, approval and implementation procedures for large-scale heat pump projects

Agora Energiewende based on AGEB (2022b). * Emissions based on the breakdown by fuel type according to AGEB (2022b) and emission factors according to UBA (2022), not weather-adjusted. Own assumptions regarding the breakdown by fuel type across the different temperature levels based on Agora Industry and Future Camp (2022).

2 Background, purpose and subject of this study

2.1 Current situation: heat generation still largely fossil-based

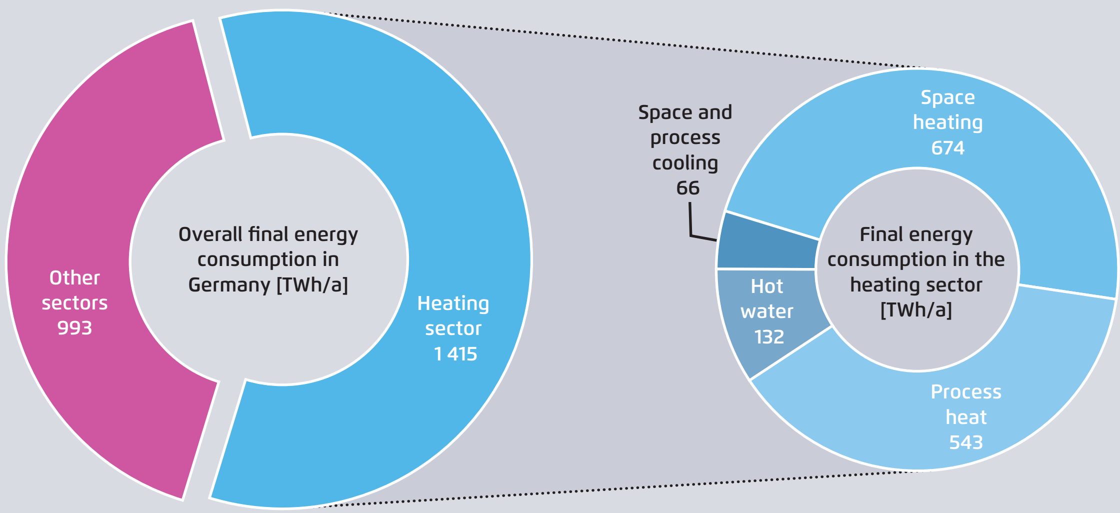
More than half of the total final energy demand in Germany is accounted for by the heating sector (as of 2021). Of the 1 415 TWh of heat demand, almost half (674 TWh) is used for space heating, while process heat accounts for another 40 percent (543 TWh per year). Hot water (132 TWh) and air-conditioning and process cooling (66 TWh) account for smaller proportions (see Figure 1) (AGEB 2022b).

Around 80 percent of the demand for heat is still met by burning fossil fuels. In the buildings sector, half of all dwellings are still supplied with fossil gas. The share of district heating in final energy demand, at about 8 percent, remains at a similar level as it was in 2011. The share of renewable energy (both directly used and indirectly via district heating) has increased only marginally, by about 0.6 percent per year, over the last three years (AGEB 2022b). In industry, too, heat generation is predominantly fossil-based, with 41 percent based on fossil gas and 20 percent based on coal (AGEB 2022b).

The resulting stagnating CO_2 emissions meant that in 2022 the greenhouse gas reduction target for the buildings sector was missed for the third year in a row (UBA 2023c).

The size, diversity and complexity of the heating sector mean that action is required in numerous

Share of heating sector in final energy consumption in Germany 2021 Figure 1



Fraunhofer IEG based on AGEB (2022b)

areas simultaneously to accelerate the decarbonisation. As explained in greater detail and depth in Chapter 3.1, it is widely acknowledged that decentralised heat pumps and climate-neutral district heating networks will be the predominant sources for heat supply in the future, while at the same time the renovation of older buildings will have to be driven forward. This study focuses primarily on how the demand for space heating and hot water will be met using district heating in Germany in the future, paying particular attention to the growing importance of large-scale heat pumps.

2.2 Purpose and subject of this study

The purpose of this study is to identify the current challenges and areas where action is needed for a rapid and extensive roll-out of large-scale heat pumps and to formulate recommendations for policy measures in the fields of energy and industrial policy.

One focus of the study is on the use of large-scale heat pumps in district heating networks. To this end, Chapter 3 looks at the opportunities and goals for the market ramp-up of large-scale heat pumps in the district heating sector and their rapidly growing importance for the currently fast-changing energy system.

Chapter 4 then examines what suitable heat sources are available in Germany and what potential they offer for the operation of large-scale heat pumps, and what challenges the exploitation of this potential entails.

Chapter 5 describes the current technological state of the art and identifies the most important components and techno-economic indicators for large-scale heat pumps and looks at selection and design criteria in an energy system that is becoming increasingly complex. This shows that the potential for the use and development of large-scale heat pumps is already bigger today than their role to date would suggest – both for district heating networks and for industrial heat generation.

Chapter 6 provides an overview of the large-scale heat pumps already available on the market today and addresses the current challenges from the perspective of the manufacturers.

Chapter 7 takes a look at the current regulatory and economic framework and the incentive mechanisms and funding schemes for investing in and operating large-scale heat pumps in Germany. In addition, this chapter contains a comparison and sensitivity analysis of the heat generation costs of various current and future projects involving large-scale heat pumps in district heating networks in Germany.

The operator perspective, i.e. the view of municipal utilities and district heating suppliers, on the current market hurdles, challenges and success factors related to the implementation of large-scale heat pump projects in Germany is explored in Chapter 8. Following on from this, the areas where action is needed for a rapid market ramp-up and where shorter planning, approval and implementation periods can be achieved are identified and described.

The study concludes with Chapter 9, which summarises the energy and industrial policy recommendations and measures derived in this study for a successful roll-out of large-scale heat pump technology in Germany, structured by thematic areas and their relevance for different stakeholders.

2.3 Large-scale heat pumps – clarification of terminology and description of the status quo

Clarification of terms used in relation to large-scale heat pumps

Heat pumps can be employed in neighbourhood, municipal, and district heating networks (all of these subsumed under the umbrella term "district heating"), as well as in industry for supplying space and process heat and hot water by using different renewable heat sources as well as waste heat from other processes. The term "large-scale heat pumps" is used in different ways, for example only for their use in district heating networks or in relation to the heating capacity of the unit. In this study, all heat pumps with a heating capacity of 500 kW or more per unit are considered large-scale heat pumps, as above this capacity different compressor technologies are usually used compared to the smaller capacity classes.

Large-scale heat pumps already available on the market today reach sink temperatures of about 90 °C to 130 °C and can therefore be used in many applications for the provision of district and local heating (see Chapter 2.4). Two major development trends should be noted here, thanks to which the range of applications for large-scale heat pumps will steadily expand in the next few years. Firstly, technical innovations introduced by manufacturers are enabling higher sink temperatures and efficiencies every year, so that more and more process heat requirements can be met by large-scale heat pumps. At the same time, better energy efficiency levels in new buildings and the continuing renovation of the existing building stock are leading to lower specific heating requirements from customers and thus also to lower flow temperatures. Lower flow temperatures, in turn, mean more efficient operation and simplify and therefore extend the use of renewable energies. These and other aspects are discussed in more detail in the chapters that follow.

In addition, heat pumps are increasingly coming to the fore in industry as a means of improving heat integration. If waste heat at a sufficiently high temperature is available, heat pumps can raise that temperature level to over 200 °C and thereby make it available for reuse.

Large-scale heat pumps are attracting increasing attention from research, industry and policymakers

In recent years, the field of large-scale heat pump technology has seen a great deal of new knowledge gained, progress made, and investment-promoting measures and legislative packages initiated in research and development, in the energy industry, and in the political arena, including:

→ **Publications and activities covering the whole of the EU, e.g.:**
  - The publication "High-temperature heat pumps", with a comprehensive description of the market for large-scale heat pumps and the current state of research and technology (Arpagaus 2019).
  - In the Technology Collaboration Programmes (TCP) for heatpumping technologies (HPT) coordinated by the International Energy Agency (IEA), Annex 58 provides a current overview of concepts and strategies for the supply of process heat from heat pumps, and Annex 59 investigates the potential of drying processes based on heat pumps (IEA 2023c, 2023a).
  - In the IEA TCP for district heating and cooling (DCP), research is currently being carried out in Annexes TS4, TS6, and TS7 on the optimal operation and maintenance of district heating networks through digital process management, the ageing performance and service life prediction of district heating networks, and the potential offered by the coupling of industrial processes and district heating networks (IEA 2018–2024, 2021–2025a, 2021–2025b).

→ **Several projects and publications in Germany, including:**
- The launch of the real-lab projects for large-scale heat pumps in district heating networks in 2021 (AGFW 2023b).
- The operational launch, the commencement of construction, the start of planning or the announcement of more than 25 new large-scale heat pump projects in Germany (see Chapter 2.4).
- The publication of the Deep Geothermal Roadmap (Bracke et al. 2022) and the Near-Surface Geothermal Roadmap (Born et al. 2022).

→ **Activities, funding programmes, and legislative initiatives on the part of the German Federal government (selection):**
- Launch of the Kompetenzzentrum Kommunale Wärmewende (Competence Centre for the Municipal Heat Transition, KWW) with the aim of establishing a nationwide networking and support platform for an area-wide municipal heat planning.
- Entry into force on 15 September 2022 of the Bundesförderung für effiziente Wärmenetze (Federal funding for efficient district heating networks, BEW), which promotes the construction of new district heating networks with a high proportion of renewable energy and the decarbonisation of existing district heating networks (see Chapter 7.3).
- Announcement of a new heat planning law which will establish municipal heat planning across the country as a central coordination and planning instrument for climate-neutral heating supply (BMWK 2023).

2.4 The role of large-scale heat pumps in the German district heating sector today

Overview of the German district heating sector

Of the total final energy demand in the heating sector in Germany in 2021, district heating generation (consumption plus grid losses) accounted for a relatively small proportion of 134 TWh or 9.5 percent (AGEB 2022a). Of this, only 29 TWh (22 percent) was supplied from renewable energy sources, mostly biomass. However, the most recent climate neutrality scenarios indicate that biomass will not play a major role in heat generation in the long term, as the sustainable potential of biomass is too low (cf. Fraunhofer ISI et al. 2022a). District heating using large-scale heat pumps, solar thermal energy and geothermal energy has played almost no role so far. In industry, the most recent figures show that 9 percent of process heat was provided via district heating networks (AGEB 2022b).

In order to achieve the goals of the heat transition, both the share of district heating networks in the heat supply and the role of large-scale heat pumps in district heating networks must be greatly increased in Germany over the next few years (see Chapter 3).

In Germany, around 465 district heating network operators (BDEW 2022) as well as numerous local heating and neighbourhood network operators currently run almost 3 800 heating networks with a total route length of 31 252 km (as of 2020). In 2020, the net expansion of district heating networks amounted to around 423 km (619.3 km new construction against 196.3 km deconstruction).

The district heating networks are operated with widely varying flow temperatures, ranging from below 60 °C to above 130 °C. At flow temperatures below about 130 °C, liquid water is circulated in the heating networks, if necessary under overpressure. For flow temperatures above about 130 °C, steam is usually used. Steam networks have the potential to transport larger amounts of heat due to the proportion of latent heat involved and are mainly used in industrial applications. In order to increase efficiency, it is becoming more common to reduce the flow temperatures in networks with liquid water and to dismantle steam networks (AGFW 2022).

Lowering the flow temperatures has the following advantages:

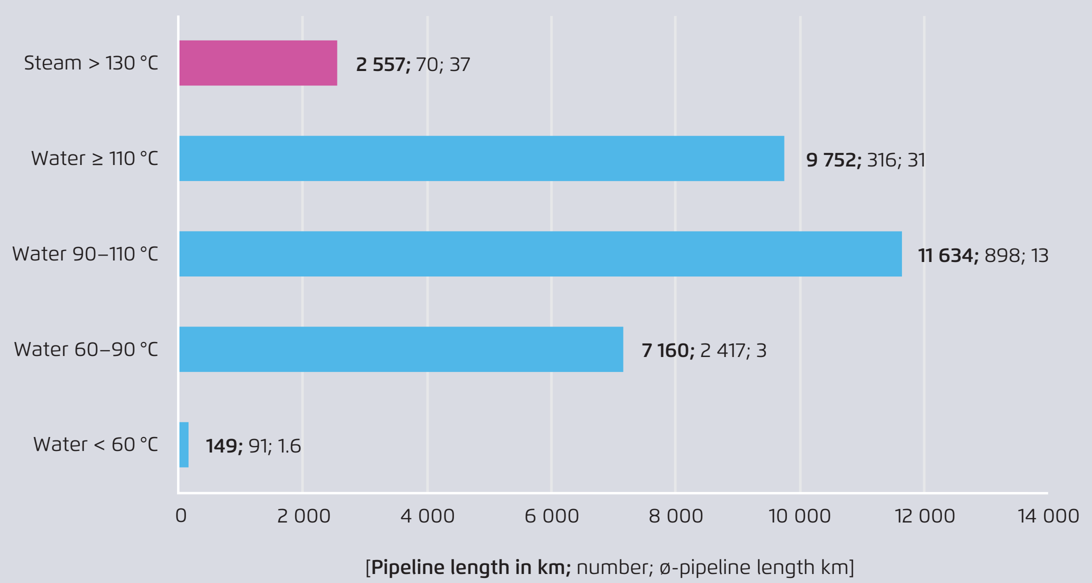
- → conduction losses are reduced (due to decreasing temperature difference relative to the surroundings);
- → the energy requirement for heat generation decreases (due to a reduction in the temperature lift required).

District heating systems operating at high temperature levels are usually very large networks: the higher the temperature level, the longer the average pipeline (see Figure 2). The roughly 900 water-based district heating systems operating in the temperature range between 90 °C and 110 °C (24 percent of all district heating systems and 37 percent of total pipeline length) have an average pipeline length of just under 13 km, and the 316 water-based systems operating at 110 °C or more have an average pipeline length of just under 31 km (8 percent of all district heating systems and 31 percent of total pipeline length). The remaining 70 or so steam-based district heating systems operating at temperatures above 130 °C in Germany have an average pipeline length as high as 36.5 km (2 percent of all district heating systems, 8 percent of the total pipeline length).

This data shows that a large number of district heating systems and distribution pipelines will have to gradually reduce their operating temperatures over the next few decades through various measures. Furthermore, it indicates the temperature levels that

Number and pipeline length of the approx. 3 800 district heating networks by flow temperature levels

Figure 2



Fraunhofer IEG based on AGFW (2022)

large-scale heat pumps and other renewable heat generators will have to reach in order to be integrated into existing district heating systems.

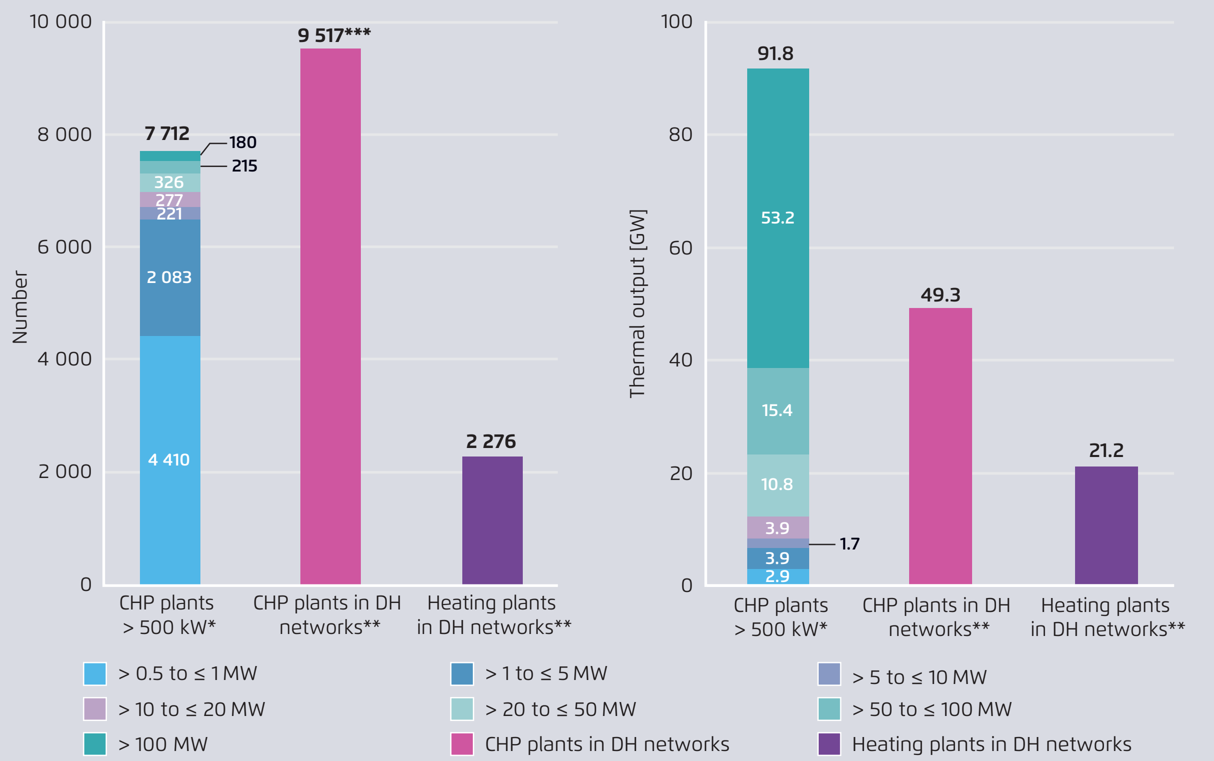
In 2020, around 70 percent of the total net heat generation in district heating systems was based on burning fossil fuels (almost 49 percent of which was fossil gas, around 14 percent hard coal, 6 percent lignite and 1 percent oil), plus the fossil (non-biogenic) proportion of waste incineration. In CHP plants, the proportion of fossil gas in net heat generation is slightly below the overall figure, at around 47 percent; whereas in heating plants, the proportion of fossil gas is significantly above the overall figure, at around 61 percent (AGFW 2022).

In 2020, CHP plants provided around 86 percent of net heat generation. In the same year, a total of almost 2 300 heating plants with a thermal output of around 21 GW (ø 9.3 MW per plant) and around 9 500 CHP plants with a thermal output of around 49 GW (ø 5.2 MW per plant) were installed in district heating systems. In addition, at the end of 2020, there were 289 heat storage facilities in district heating systems in Germany with a total heat storage capacity of around 66 gigawatt hours (GWh) (ø around 230 megawatt hours (MWh) per heat storage facility) (AGFW 2022).

The majority of existing heat generation plants must be modernised and converted to climate-neutral fuels

Number and thermal output of CHP plants larger than 500 kW and of CHP plants and heating plants in district heating systems

Figure 3



Fraunhofer IEG based on *BNetzA (2023a), **AGFW (2022). ***includes multiple entries if more than one energy source was used in heating plants.

(mainly biomass or green hydrogen for CHP) or replaced by renewable heat generation technologies by 2045. How this transformation requirement is to be divided between the different output classes and existing heating networks is not exactly clear from the publicly available data. However, the different output classes in the range of 0.5 MW and above in the CHP plant stock can provide some orientation (see Figure 3).

Based on the simplified assumption that replacement facilities using renewable energy and waste heat will have to be created in the next two to three decades for the existing, largely fossil-fuelled CHP plants and heating plants, Figure 3 gives an approximate picture of the level of investment that will be required to ensure that a sufficient number of large-scale heat pumps with the necessary capacity is available.

Large-scale heat pumps in Germany: Overview of existing and planned capacity

Large-scale heat pumps currently play only a subordinate role in Germany's heat supply. While in other European countries large-scale heat pumps have played an important role for decades already (e.g. Scandinavia and Finland), only comparatively few large-scale heat pumps have been installed in Germany to date in both the district heating and industrial sectors. Due to the limited significance of large-scale heat pumps in Germany in the past, little relevant statistical data is publicly available.

Fraunhofer IEG therefore conducted its own research, contacted selected district heating providers as well as manufacturers and operators of large-scale heat pumps, and evaluated the information available from relevant trade associations (Working Group District Heating; Arbeitsgemeinschaft Fernwärme (AGFW) and Federal Heat Pump Association; Bundesverband Wärmepumpe (BWP)). The results of the research do not claim to be exhaustive but provide an up-to-date overview of the number of large-scale heat pump projects either already in operation or currently planned in Germany.

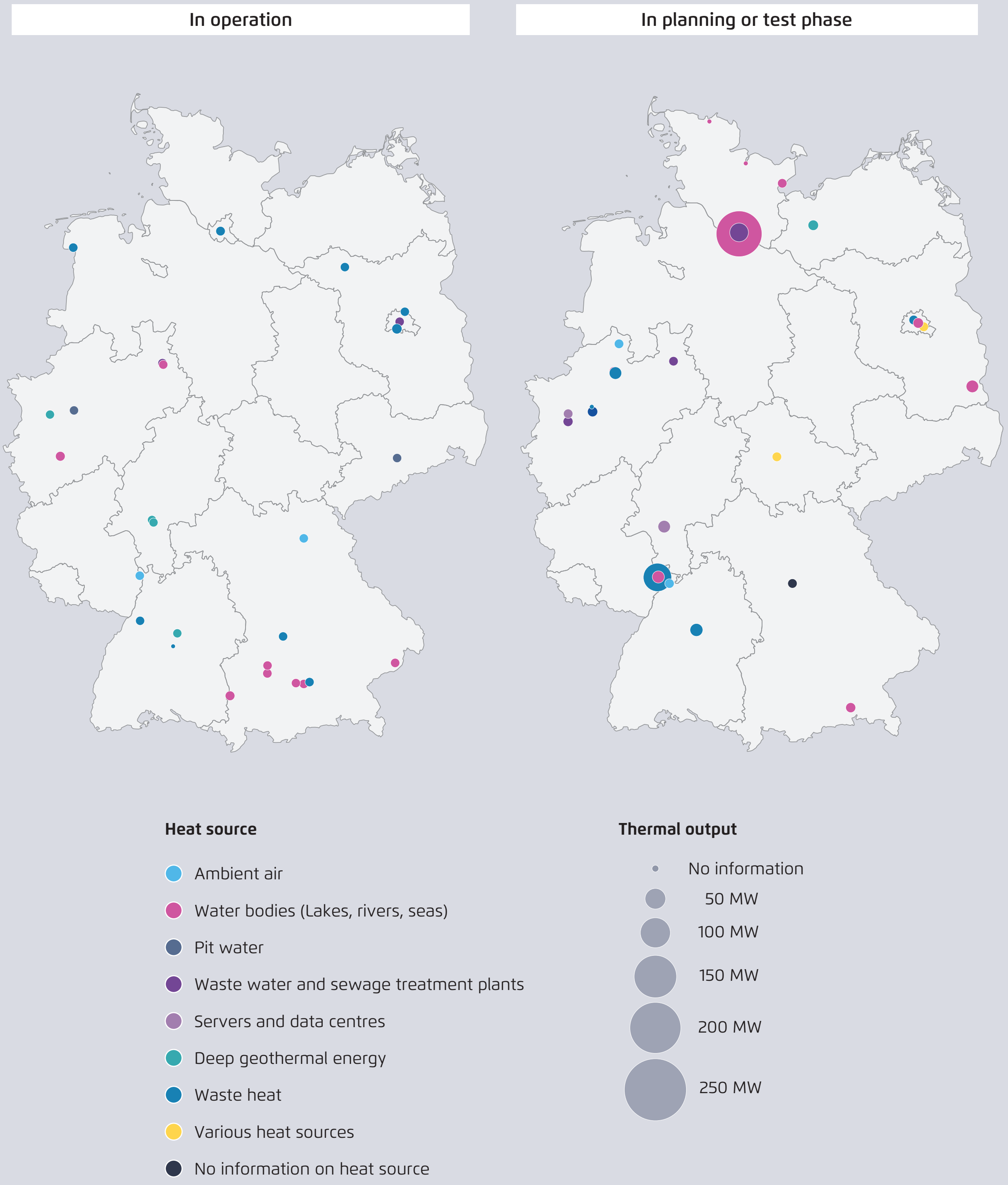
This research shows that at the beginning of 2023 there were at least 30 heat pump installations with a thermal output of 500 kW or more in operation in Germany, together providing a total output of approximately 60 MW. In addition, according to information from Fraunhofer IEG, at the beginning of 2023 at least 30 further large-scale heat pump projects with a total output of around 600 MW were already either under construction or in planning. Large-scale heat pump projects for which the site is known are shown in Figure 4. Furthermore, there are currently several announced plans for large heat pump projects, and others that have not yet been made public, with individual outputs in the single to triple-digit MW range, which are currently the subject of feasibility studies.

For those large-scale heat pumps (projects) for which information is also available on the maximum flow temperature to be supplied by the units, Figure 5 provides an overview of the individual outputs and heat sources.

Among the projects researched, waste heat and water bodies are the most common sources of heat; projects using wastewater and pit water are less common, and ambient air, deep geothermal energy and waste heat from servers and data centres have been used in only a few cases. Possible explanations for this pattern are explored in more detail in Chapter 4.

Currently, there are no heat pumps in operation in Germany in the range above 10 MW. Among the plants in planning there are several with a thermal output of more than 10 MW and flow temperatures of 80 °C to 125 °C. These plants mainly use water (river, sea or lake water) as a heat source, but some use wastewater and waste heat. In the lower output range and in the lower flow temperature range, there are probably more projects in planning than captured

Existing and planned large-scale heat pump projects in Germany — Figure 4



Fraunhofer IEG (2023)

by the research, as it can be assumed that not all projects in this range are announced by e.g. a press release, especially in comparison to projects with high thermal outputs.

With regard to flow temperatures, the large-scale heat pumps surveyed cover the entire range from 35 °C to 125 °C. Large-scale heat pumps for district heating reach flow temperatures of 80 °C to 125 °C. Heat pumps with flow temperatures lower than 80 °C are mainly used to supply local heating networks, decentralised heating and process heat.

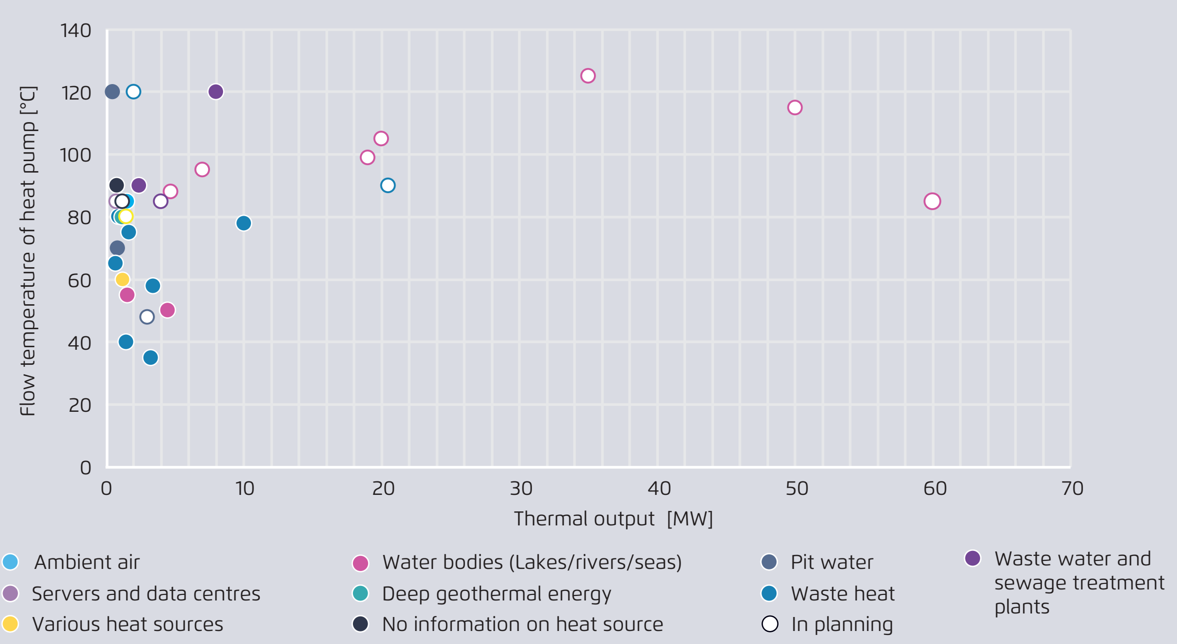
Discussions between Fraunhofer IEG and project developers and manufacturers of large-scale heat pumps indicate that the project momentum in the industrial sector is currently at least as high as in the district heating sector and that heat pumps operating at even higher temperatures (see Figure 42 in Appendix A.3) are also being planned there. In the industry sector, however, the data is not very transparent. From publicly available data, only one project in planning could be identified:

→ Large-scale heat pump plant in the chemicals industry with 120 MW for steam generation (BASF 2022).

The data is somewhat easier to access for the projects that have already been implemented. The following industrial projects were found:

→ a large-scale heat pump system with a total of 10 MW and 80 °C flow temperature, used in the timber industry (Jakobs and Stadtländer 2020),

Heat sources and individual outputs of existing and planned large-scale heat pumps in Germany* — Figure 5



Fraunhofer IEG based on AGFW (2022). * There is only a small number of projects in the range 0.5 to 1 MW. This can be explained by the fact that this performance range is often delivered by interconnected heat pumps from smaller performance classes. Since in these cases the individual heat pumps have a thermal output of less than 500 kW and thus cannot be classified as large-scale heat pumps according to the definition in this study they are not considered here.

- → a large-scale heat pump with a thermal output of 3.2 MW and a flow temperature of 35 °C for decarbonising a drying process in the food industry, which has already been in operation since 2010 (Jakobs and Stadtländer 2020), and
- → a large-scale heat pump for preheating process water to 75 °C using 1.7 MW (Jakobs and Stadtländer 2020).

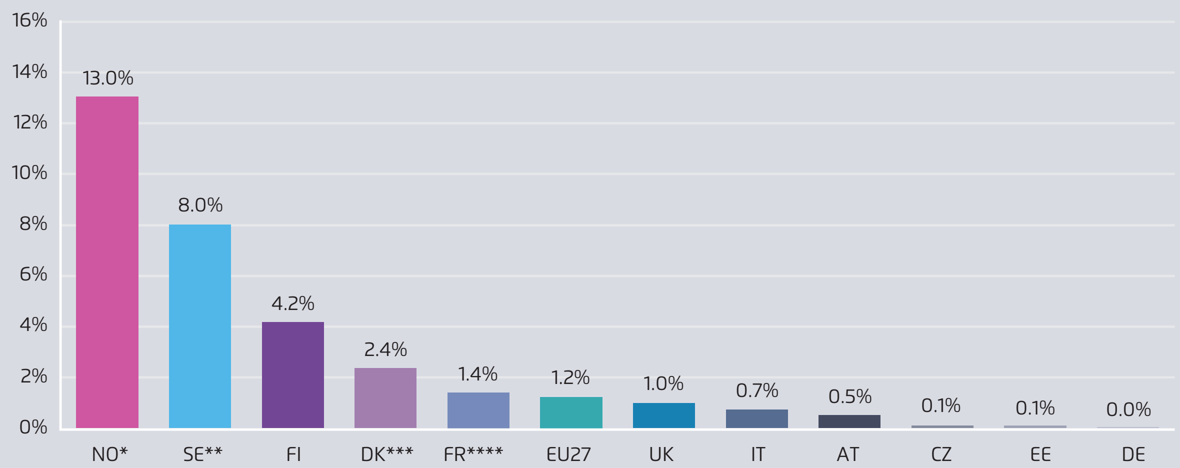
Appendix A.1 contains an overview of the known large-scale heat pump projects, of which a small selection is additionally described in a little more detail as individual profiles.

2.5 Significance and success factors of large-scale heat pumps in Europe

In other European countries, heat pumps in the buildings sector and large-scale heat pumps in the district heating sector are more common than in Germany. In addition to the frontrunners Norway (NO), with a share of around 13 percent of district heating supply from large-scale heat pumps, and Sweden (SE), with a share of over 8 percent, Finland (FI), Denmark (DK) and France (FR) also have above-average shares of heat generation from large-scale heat pumps in the district heating sector. In the district heating systems in Great Britain (UK), Italy (IT) and Austria (AT) there are also some large-scale heat pumps already in use. In the other European countries, large-scale heat pumps, with shares at or near 0 percent, have so far played just as negligible a role as in Germany. Therefore, the average share of large-scale heat pumps in the group of 27 EU countries was 1.2 percent in 2020 and will be only marginally higher at the beginning of 2023 (see Figure 6).

There are several reasons why large-scale heat pumps do or do not play a greater role in other countries. However, climatic conditions and the number of heating degree days per year are not among them, as Norway and Sweden demonstrate.

European countries with the highest shares of large-scale heat pumps in district heating supply (data from 2020/2021) Figure 6



Fraunhofer IEG based on Bacquet et al. (2022), Euroheat & Power (2022). * Norsk Fjernwarme (2023) (calculated from the utilised ambient heat using the COP figures for Sweden). ** SCB (2022). *** Danish Energy Agency (2022). **** FEDENE und SNCU (2022)

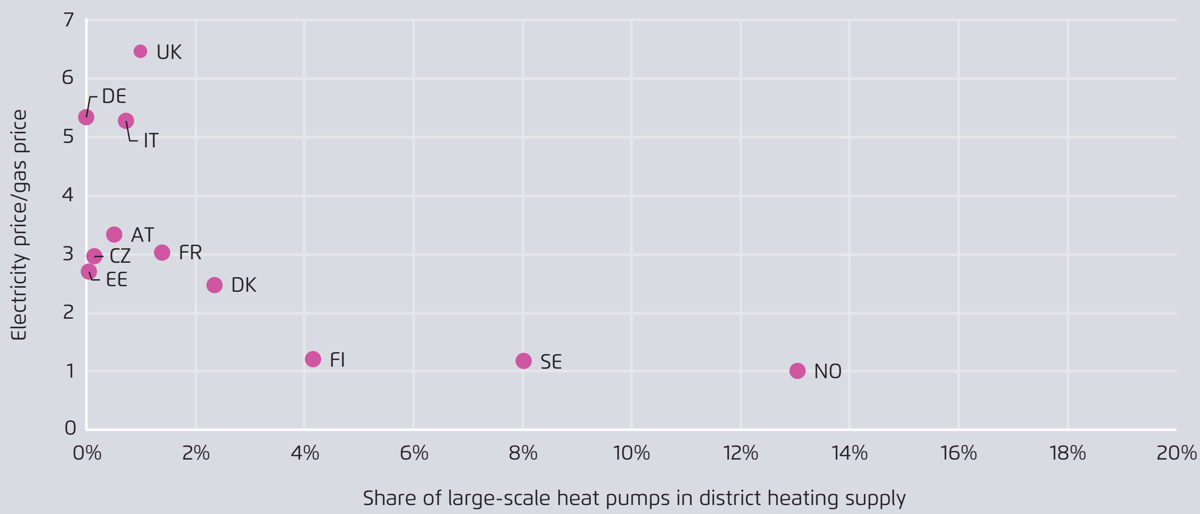
Rather, the relevant criteria, which have an impact above all in combination, are the following:

- The ratio of electricity costs to gas costs: The lower this ratio is, the more attractive the operation of heat pumps becomes. The energy and economic policy frameworks and priorities exert a major influence on this.
- Whether and at what level carbon pricing is applied: Effective carbon pricing, as in Sweden, for example, makes the use of low-carbon or zero-carbon energy sources (especially electricity from renewables) relatively more attractive.
- The role of fossil fuels such as fossil gas, hard coal, and lignite and also of nuclear energy in energy production: The commitment of politicians, business and the general public – as in Denmark, for example – to reducing the dependence of the energy supply, especially for heating, on fossil energy sources and imports, and to transforming the energy supply, is also important.

The ratio of the electricity price to the gas price in selected countries over the last few years is compared in Figure 7. This shows that the three countries – Norway, Sweden and Finland – in which the market shares of large-scale heat pumps are the highest also have a low ratio of electricity to gas prices. At the same time, the price ratios in the other countries suggest that the ratio of electricity to gas prices alone is not a sufficient criterion for a significant role for large-scale heat pumps in district heating systems.

Rather, it is crucial for the transformation of heat supply that clear goals and priorities are set in energy and economic policy. Furthermore, the economic framework and incentives must be aligned consistently in such a way that they do not send conflicting investment signals. Finally, planning certainty must be sufficiently high over the entire lifetime of centralised heat generation systems. These considerations are discussed in more detail in Chapters 6, 7 and 8 and summarised in the recommendations for action (Chapter 9).

Ratio of electricity to gas prices in selected countries* Figure 7



Fraunhofer IEG based on Eurostat [etc.] * incl. taxes and levies, charges, surcharges and fees, excl. VAT on average for the years 2017 to 2021 for the purchasing categories „Range ID: 2 000 to 20 000 MWh electricity“ and „Range I4: 100 000 to 1 000 000 GJ gas“

Sweden, Finland, Denmark and Norway stand out from the rest of Europe in terms of the total thermal output of large-scale heat pumps already installed and their relative contribution to district heating supply (Euroheat & Power 2022). What distinguishes these countries with regard to the special role of large-scale heat pumps, and which policy decisions and/or energy industry framework conditions might have been decisive for this development in the district heating sector, will be considered below.

The role of district heating systems in ensuring a secure, affordable and sustainable energy supply is evaluated more positively than on average in these countries (Breitschopf et al. 2022). One possible reason for the greater public acceptance for district heating systems, as well as for large-scale heat pumps, may lie in the many years of accumulated experience. Often these investments were made many years ago and have been performing well ever since. For example, a number of large-scale heat pumps were installed in district heating systems in Sweden between 1980 and 1990 already (Euroheat & Power 2022).

In contrast to other European countries, end consumers in Sweden, Denmark and Norway have comparatively high annual heating costs in absolute terms (Breitschopf et al. 2022). This also applies to Germany and is mainly due to the fact that in these countries the demand for heat is higher on an annual average due to the comparatively low outside temperatures.

The fact that Northern Europe is nevertheless leading in the roll-out of large-scale heat pumps may be due principally to the fact that in all four countries (Sweden, Denmark, Norway and Finland) both a carbon tax for the heating market (since the beginning of the 1990s) and a subsidy for investment costs for large-scale heat pumps have been in place for some time (Euroheat & Power 2022). In Sweden, the carbon tax on fossil fuels for industry outside the EU ETS is now at €122 per tonne of CO_2 (Government Offices of Sweden 2023). In Finland, the operating costs of district heating systems are also still subsidised (Euroheat & Power 2022).

The example of Denmark also shows the positive effects of politically driven heat planning and the associated early and ongoing participation of diverse stakeholders such as municipal energy suppliers, planning offices, public authorities and administrative bodies. This can not only simplify and accelerate approval processes but can also lead to a higher level of awareness and thus higher public acceptance for district heating systems (Breitschopf et al. 2022). Denmark is therefore considered a role model for successful heat planning and a successful transition (Breitschopf et al. 2022).

3 Climate neutrality scenarios and the role of district heating and large-scale heat pumps

3.1 Pathways towards an economically efficient energy and heat transition

Overview of current energy system and climate neutrality studies

Germany is committed to achieving climate neutrality by 2045 as stated in the Federal Climate Protection Act[2] (Bundes-Klimaschutzgesetz, KSG), as amended in June 2021. Specific decarbonisation targets were set out for individual sectors to make the Act more binding and to increase its scope. In order to provide guidance for the stakeholders affected by the energy and heat transition, several energy system and climate neutrality studies or long-term scenarios were prepared and published in 2021 and 2022.

In 2021, the so-called "Big 5" climate neutrality studies were published:

- „Climate-neutral Germany 2045", conducted by Stiftung Klimaneutralität, Agora Energiewende and Agora Verkehrswende (Prognos et al. 2021)
- „Climate pathways 2.0 – an economic programme for the climate and the future", commissioned by the Federation of German Industries (BDI) (BCG und BDI 2021)
- The pilot study „Climate neutrality – a new start ", conducted by dena (dena 2021)
- „Long-term scenarios for the transformation of the energy system in Germany 3" for the Federal Ministry for Economic Affairs and Climate Action (Bundesministerium für Wirtschaft und Klimaschutz, BMWK) (Fraunhofer ISI et al. 2021)
- „Germany on the path to climate neutrality 2045", from the Kopernikus project Ariadne, supported by the Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung, BMBF) (PIK 2021)

These studies describe, among other things, the transformation paths and the mix of technologies and policy measures that could be used to achieve the climate protection goals in the most cost-effective way from an economic perspective. They confirm that achieving climate neutrality by 2045 or 2050[3] in Germany will require the increased use of renewable electricity in all sectors, which will entail an vast expansion of wind and photovoltaic capacities. Beyond this, the studies also agree that heat pump technology and decarbonised district heating systems will play an important role in achieving the goals in the buildings sector (PIK 2022).

2 The KSG was passed by the Bundestag on 19 November 2019. The climate protection and sector targets set out in the Climate Plan 2050 were enshrined in law for the first time in the KSG. In its ruling of 24 March 2021, the Federal Constitutional Court obliged the legislator to extend the KSG for the periods from 2031 onwards. This, together with a tightening of targets at EU level, led to an amendment to the KSG, which was passed by the Bundestag on 24 June 2021

3 The „Long-term scenarios for the transformation of the energy system in Germany 3" by Fraunhofer ISI et al. 2021 were drawn up before the amendment to the KSG, so they depict the path to climate neutrality by 2050 in accordance with the targets of the original KSG from 2019.

Since the "Big 5" climate neutrality studies were conducted, there have been significant developments in energy policy, which are discussed below.

Current developments and their significance for the research carried out for this study

The politically mandated expansion of renewable energies largely defines the electricity system of the future. With the reform of the Act for the expansion of renewable energies (Erneuerbare-Energien-Gesetz, EEG), the new German government has set a new target: by 2030, 80 percent of gross electricity consumed is to come from renewable energy sources (previously 65 percent). At the same time, the estimate of future electricity consumption was raised to 750 TWh. Concomitantly, the expansion targets for wind and solar energy were increased.

The study "Climate-Neutral Electricity System 2035", conducted by Agora Energiewende (Agora Energiewende, Prognos, Consentec 2022), sets out how these goals can be achieved and what challenges there are regarding the necessary measures for infrastructure expansion (renewable energy and electricity grids) and for making the electricity demand side more flexible.

The accelerated expansion of electricity generation from renewable energy sources also improves the CO_2 balance of all electricity-consuming plants and systems, such as heat pumps and electric vehicles. If these are then also operated or charged flexibly, primarily at times when the share of renewable energy in the electricity mix is particularly high, their CO_2 balance is further improved (on flexibility and sector coupling in the future energy system, see Chapter 3.2).

The fossil energy crisis underscores the need for an accelerated heating transition. The economic turbulence in the energy sector in 2022 caused by Russia's war of aggression against Ukraine clearly showed the dependence of the European Union – and of Germany in particular – on fossil fuels, and especially on fossil gas. In order to quickly and sustainably reduce dependence on fossil fuels from Russia, in May 2022 the EU Commission unveiled the REPowerEU plan. Among other things, this plan calls for the industrial consumption of fossil gas in Europe to be almost halved by 2030. The study "Power-2-Heat: Fossil gas Savings and Climate Protection in Industry" (Agora Industry and FutureCamp 2022) describes the great potential offered by the electrification of industrial process heat, which clearly illustrates the importance of large-scale heat pumps for the decarbonisation of industry.

The T45 scenarios serve as the basis for the investigations carried out for this study. In order to take into account the latest energy policy developments, it was decided to use the updated "Long-term scenarios for the transformation of the energy system in Germany 3" (Fraunhofer ISI et al. 2022b) as the basis for this study. In the five updated long-term scenarios ("T45 scenarios"), different paths for decarbonising Germany by 2045 are set out. In the three main scenarios, an increased use of either electricity (T45-Electricity), hydrogen (T45-H_2) or synthetic hydrocarbons (T45-PtG/PtL) is assumed. For the T45-Electricity scenario, a sub-scenario at lower energy efficiency (T45-RedEff) and a sub-scenario at lower fossil gas consumption (T45-RedGas) are also provided. All T45 scenarios take into account the targets of the amended KSG (Climate Protection Act) (including climate neutrality in 2045 and stricter sector targets) as well as the increased expansion targets from the Renewable Energy Sources Act 2023. Among the T45 scenarios, the T45-Electricity scenario incurs the lowest cumulative costs for the national economy. More synthetic hydrocarbons and less efficient buildings mean higher overall costs for the system. A comparison of the T45 main scenarios with the results of the other climate neutrality studies listed here shows that factoring in the ambitious energy policy goals and measures adopted in 2021 and 2022 for the year 2030 leads to a significant increase in renewable electricity generation (in terms of both proportion and total energy output) and a significant reduction in absolute greenhouse gas emissions (see Figure 8). This underlines the necessity of using climate neutrality scenarios that are as up-to-date as possible.

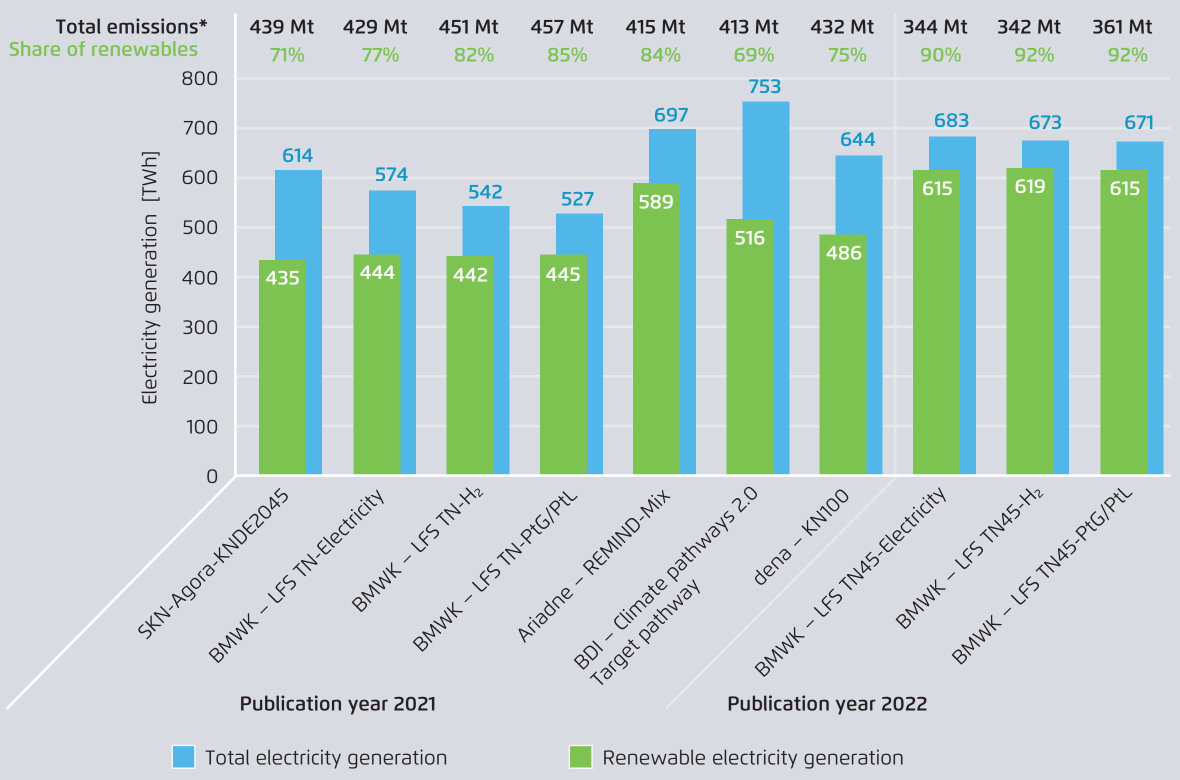
Of the studies considered, the T45 scenarios from the BMWK (Federal Ministry for Economics and Climate Action) are the most up-to-date and have the widest application scope. Since the findings from the long-term scenarios are also to be incorporated into the BMWK's new system development strategy for the energy sector, the T45 main scenarios were selected as the basis for further investigations in the context of this study.

The role of large-scale heat pumps in scenarios for the heat transition

Achieving a climate-neutral buildings stock by 2045 requires a significant expansion of district heating systems and a large increase in the number of heat pumps. The optimisation targets for all T45 scenarios are configured in such a way that a climate-neutral buildings sector is achieved by the year 2045. This also includes assumptions regarding the continuous reduction of the specific final energy demand of buildings, which is achieved through energy-saving renovation measures and the use of more efficient heating technologies. For the T45-Electricity scenario, the renovation cycles used in the modelling

Key data on electricity generation from renewables in 2030 – comparison of different energy system studies

Figure 8



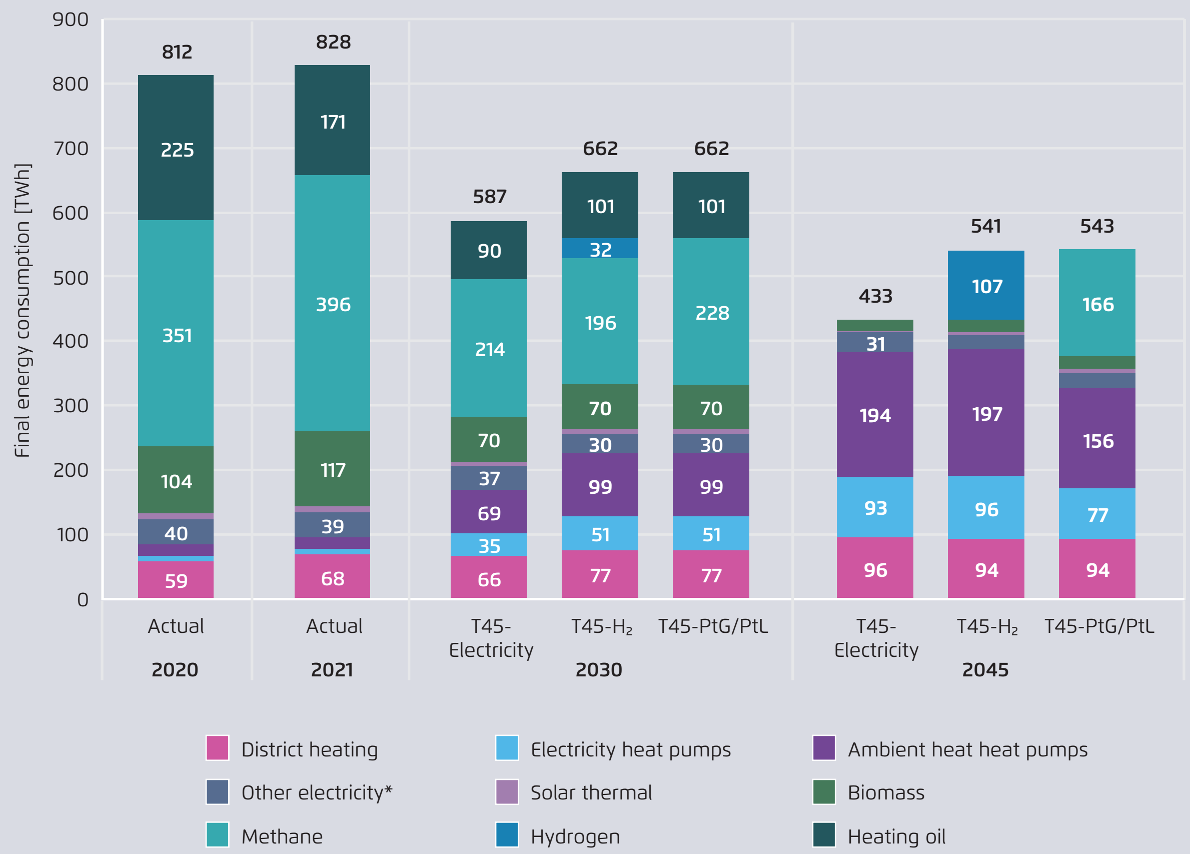
Fraunhofer IEG based on Prognos et al. (2021), PIK (2022), Fraunhofer ISI et al. (2021), Fraunhofer ISI et al. (2022b).
* Greenhouse gas emissions incl. land use, land use change and forestry (LULUCF)

result in an average renovation rate of 1.95 percent per year, and for all other T45 scenarios in an average renovation rate of 1.49 percent per year, with corresponding effects on the final energy savings that can be achieved by 2045. The heat supply is dominated by decentralised heat pumps and district heating, which includes heat generation from large-scale heat pumps (see Figure 9).

Electrification of the heat supply also plays a major role in the decarbonisation of the industrial sector. With regard to the economically efficient transformation of the industrial sector, the T45 scenarios show that, in addition to the use of climate-neutral synthetic fuels, the electrification of many industrial processes is a key factor. Industrial electricity consumption therefore increases significantly in all T45 scenarios. Part of this additional electricity consumption results from (process) heat supply from electrode boilers and large-scale heat pumps which are not part of district heating systems. At the same time, district heating demand in the industrial sector also increases by a factor of 1.4–1.9 by 2045 (compared to 2020) in the T45 scenarios, to which large-scale heat pumps can also make a decisive contribution in the future.

Development of final energy consumption in the buildings sector

Figure 9



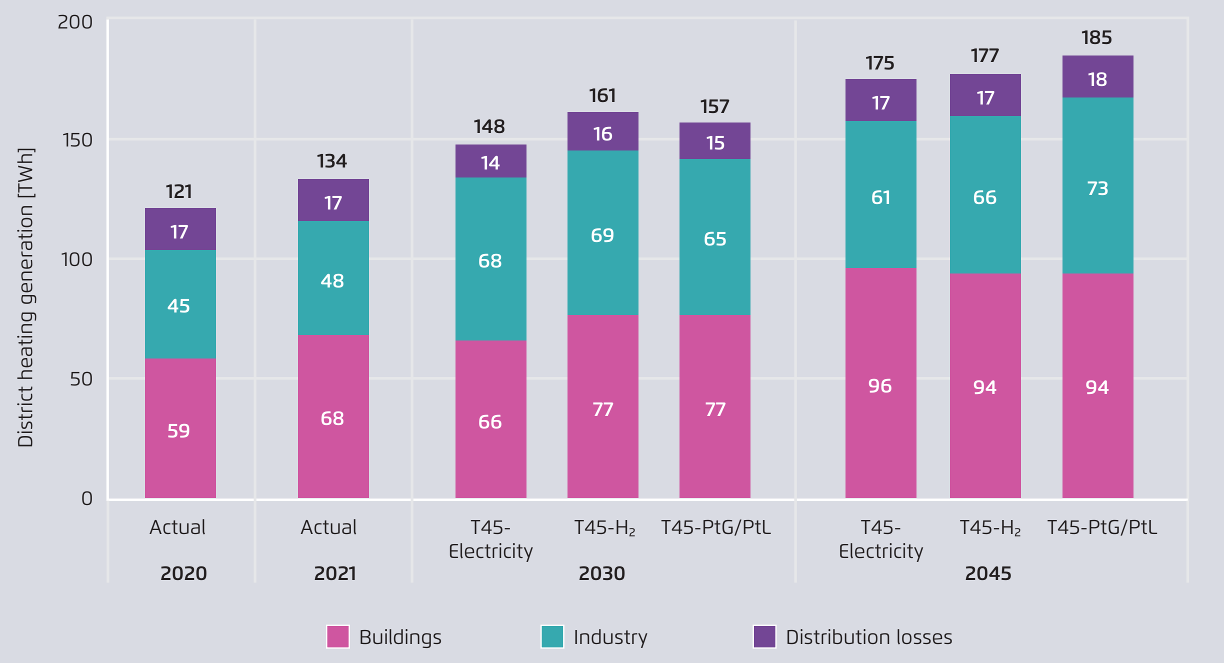
Fraunhofer IEG based on AGEB (2022b), Fraunhofer ISI et al. (2022b), Mellwig et al. (2021). * Direct heating, domestic hot water and auxiliary energy

Across all scenarios, there is a clear increase in the total district heating supply – for both the buildings and the industrial sectors. Starting at 116 TWh in 2021, the supply of district heating increases strongly in the T45 scenarios. Depending on the optimal energy mix in the industrial sector, district heating supply in 2045 in the different T45 scenarios ranges from 158–167 TWh, which corresponds to an increase of 36 to 44 percent compared to 2021 (see Figure 10).

District heating supply for the buildings sector is at a similarly high level of 94-96 TWh in 2045 (an increase of 38 to 41 percent over 2021) in all scenarios. This corresponds to an average increase in supply of 1.1 TWh per year in Germany (+ 1.5 percent per year). However, since the heating demand from individual buildings is steadily decreasing over the same period due to efficiency and renovation measures, an increase in district heating supply in the buildings sector requires extensive network densification and expansion measures. Specifically, the T45 scenarios show that the number of new heating network connections would have to roughly triple by 2045 (increase by a factor of 2.9–3.1) and that this would require about 130 000 to 150 000 new network connections each year (+ 8 percent per year) as well as an expansion of 800 km of distribution network pipelines (+ 2.5 percent per year) (Mellwig 2022).

Development for district heating generation (end supply plus distribution losses) in the T45 scenarios

Figure 10



Fraunhofer IEG based on AGEB (2022a), Fraunhofer ISI et al. (2022b)

Based on a simplified assumption of investment costs of 500–1 000 euros per metre of pipeline,[4] this amounts to an annual investment volume of 400–800 million euros for the expansion of the distribution network in the district heating sector alone.[5]

By way of comparison, in 2020, the net expansion in district heating networks according to the AGFW was around 423 km, which corresponds to approximately half of the annual expansion that will be required in the future.

Enabling lower network operating temperatures to gradually reduce the average temperature level of the entire district heating network will become a key feature of future network densification and expansion projects.

In 2045, large-scale heat pumps could already be providing more than 70 percent of district heating. Across all T45 scenarios, it can be seen that a rapid expansion of heat generation from large-scale heat pumps is crucial for an efficient energy system, and that they have the potential to dominate district heating systems in the near future. The T45 scenarios show that at the same time, heat generation from CHP plants will decline sharply and that from around 2040 onwards only a small contribution from CHP, from the combustion of substitute fuels, biomass and green hydrogen, will be needed for peak load and backup capacities (see Figure 11).

Little or no consideration has been given in the T45 scenarios to the large potential for waste heat utilisation from industry, data centres and electrolysers (which, however, are mainly located near the sites of large wind farms and ground-mounted photovoltaic plants because of the optimisation algorithms). The inclusion of these additional waste heat sources could – provided they are economically viable – reduce the considerable need for large-scale heat pumps slightly further.

In order for large-scale heat pumps in district heating to fulfil their potential contribution to the energy transition, an average expansion of at least 4 GW per year is necessary up until 2045. In the T45 scenarios, the energy output from large-scale heat pumps will amount to at least 90 GW by 2045 (Figure 12).

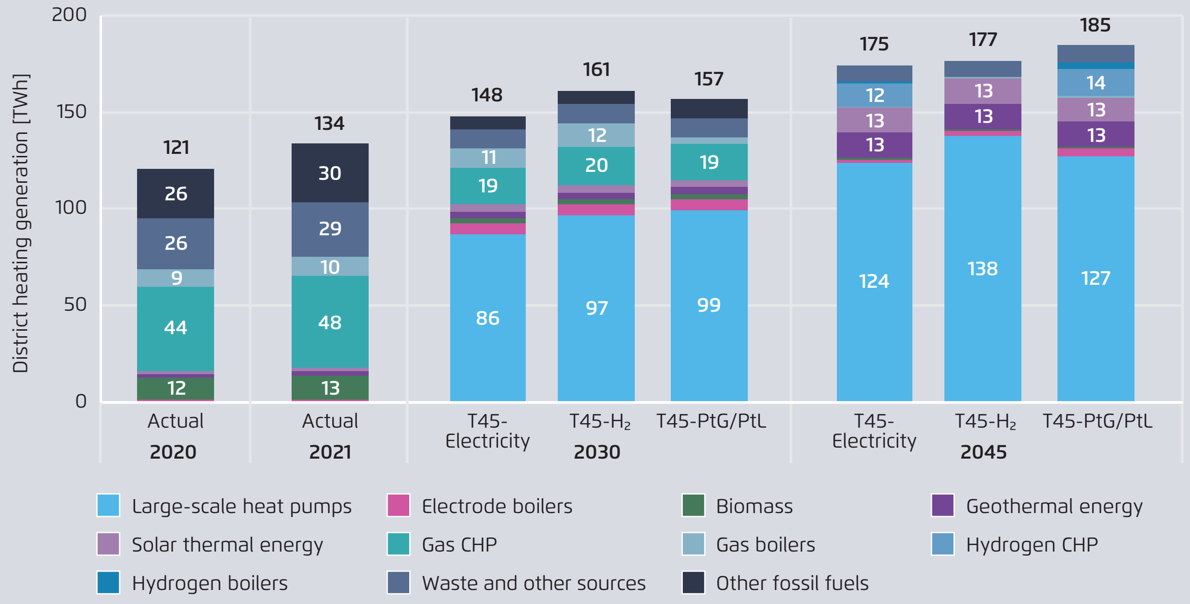
In comparison, Germany is starting from near zero, given that the capacity of large-scale heat pumps in operation and planned at the beginning of 2023 amounts to less than 1 GW (see Chapter 2.4). This means that in the district heating sector alone there will be an annual market potential for new large-scale heat pumps of at least 4 GW up until 2045. Moreover, this figure does not take into account the demand for large-scale heat pumps for industrial enterprises not connected to district heating systems.

4 Illustrative assumption based on the cost range for conventional district heating networks and low-temperature heating networks with various output ranges and construction requirements from the technology catalogue for local heat planning in Baden-Württemberg (KEA-BW 2022).

5 Approximately 1.7 billion euros were invested in the gas distribution network in 2021. Of this, around €1.1 billion was invested in new construction, expansion and extension and €0.6 billion in the maintenance and renewal of gas distribution networks (BNetzA 2023b).

Development for the technology and fuel mix for district heating generation in the T45 scenarios

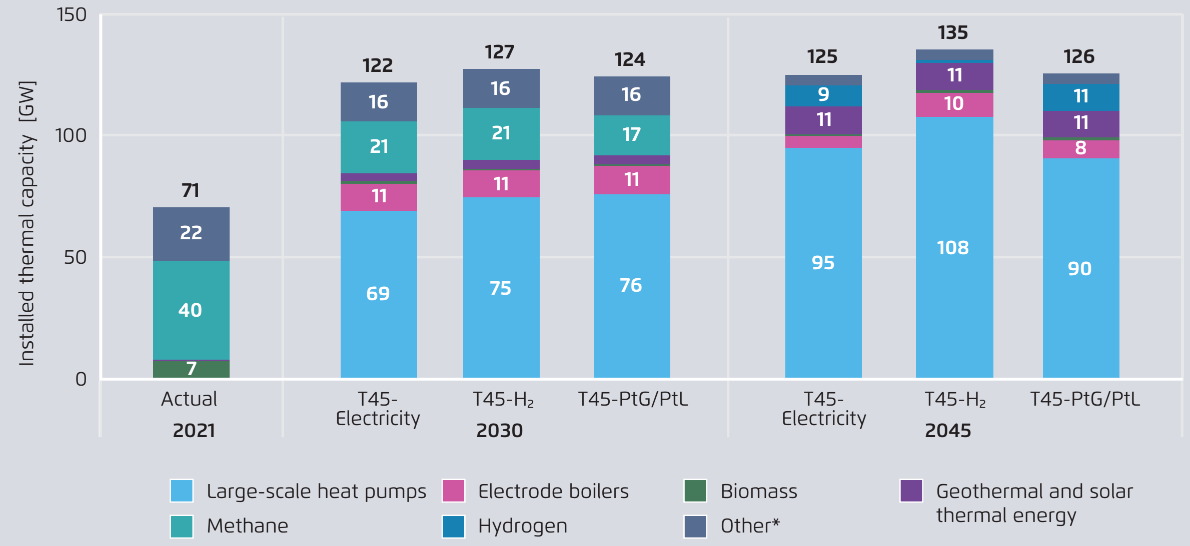
Figure 11



Fraunhofer IEG based on AGEB (2022a), AGEE (2022), AGFW (2022), Fraunhofer ISI et al. (2022b)

Development for installed thermal capacity in district heating

Figure 12



Fraunhofer IEG based on AGFW (2022), Fraunhofer ISI et al. (2022b). * Lignite, hard coal, waste and other fossil fuels

3.2 Operating large-scale heat pumps in a flexible and system-supporting way

Basic principles of a flexible power and heat system

District heating systems traditionally have several different heat generation facilities and technologies, and can also to some extent use the pipeline network for heat storage. Increasingly, power-to-heat plants and large-scale heat storage units are also being integrated into district heating systems. District heating suppliers thus have the opportunity to continuously optimise the use of their heat generation portfolio depending on the supply and demand situation on the electricity and heat markets and subject to other technical and regulatory restrictions.

The prerequisites for electricity generation based 100 percent on renewable energy in 2035, in addition to the expansion of renewable energy and the electricity grids, are greater flexibility, more storage capacity and more sector coupling in the system as a whole.

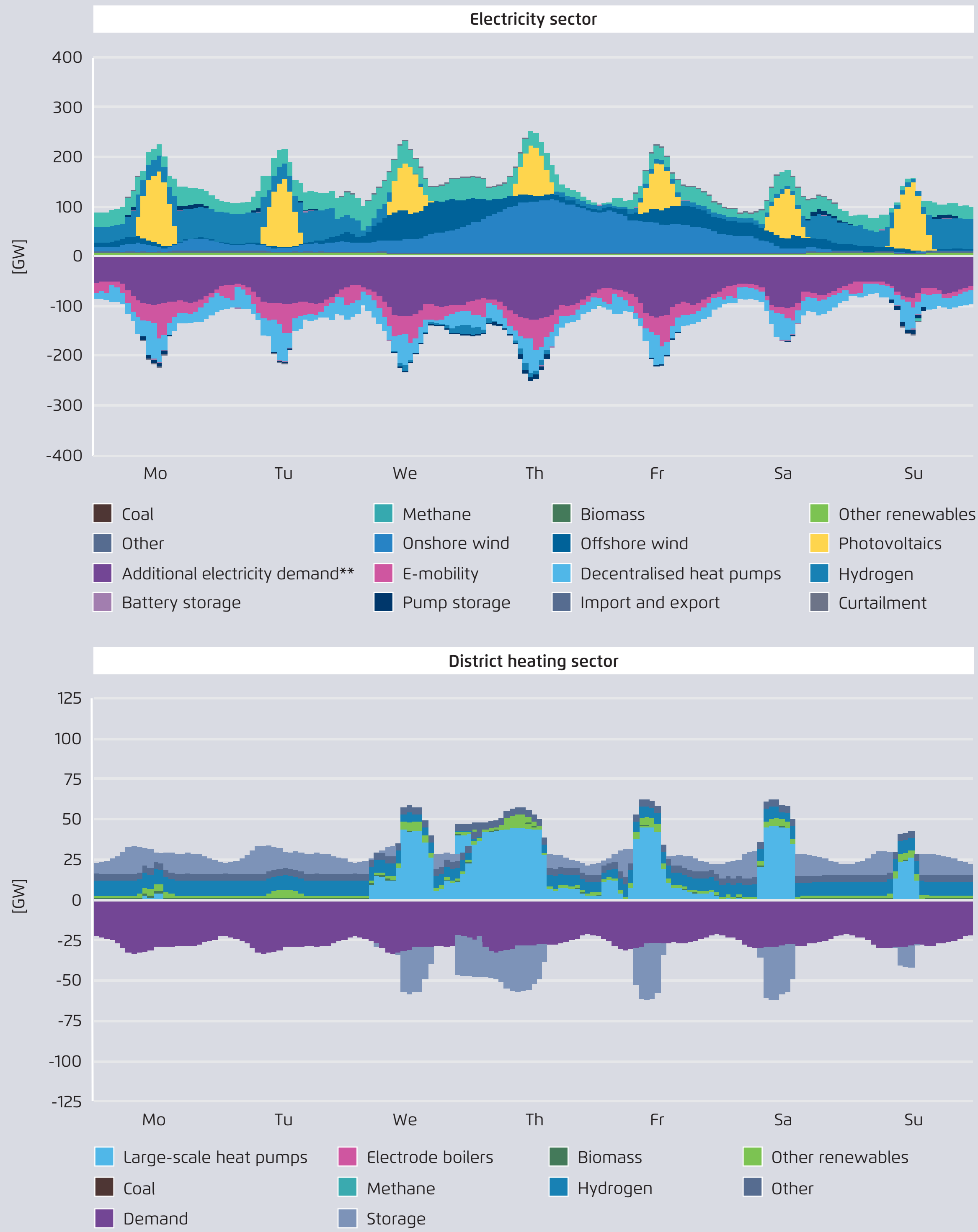
The design of the electricity market of the future must encourage and enable the operation of large-scale heat pumps in a way that supports the system overall. However, achieving the cost advantages of the increased use of large-scale heat pumps as identified in the optimisation models of the T45 scenarios presupposes that these and other flexible electricity consumers and energy storage systems can actually benefit from the low electricity production costs of wind and solar plants. For example, flexible network use charges and guarantees of long-term favourable electricity procurement costs are important if the operation of flexible electricity consumers is geared both to the availability of wind and solar generated electricity and to the grid load in a way that supports the system overall.

The extent of the flexibility requirements in the electricity and district heating sector in the future, and the resulting requirements for the operation of large-scale heat pumps, are shown below, based on the simulation results from the T45-Electricity scenario for a typical winter week and summer week in the year 2045. The winter week of the future, just as it is today, is characterised by high heat demand and by wind power generation above the annual average, but also by a comparatively low production rate from photovoltaic installations. In summer, on the other hand, there will naturally only be a very limited demand for district heating. At the same time, there will often be very high peaks of electricity production from renewable energy sources during the day, especially from photovoltaic plants, which will still considerably exceed even the growing final demand in the electricity sector.

Operating large-scale heat pumps in a way that supports the power system

In winter, large-scale heat pumps will in future dominate the highly flexible portfolio of heat generation systems and will be supplemented by solar and geothermal energy, climate-neutral CHP and heat storage systems. Figure 13 shows the feed-in and demand load curves in the electricity and district heating sectors for a typical winter week in 2045 under the T45-Electricity scenario. This clearly demonstrates that in a cost-optimal energy system, large-scale heat pumps should always be used when electricity production (from renewables) is high and favourable electricity supply costs can be obtained. The heat production that is then not needed to cover simultaneous demand for heat is temporarily stored in large-scale heat storage facilities. At times when there is a demand for heat but renewable electricity production is low and the wholesale electricity market price is consequently higher, the heat demand is met from the heat storage facilities and via other heat generation technologies, for example CHP plants using biomass, substitute fuels or green hydrogen.

Operation of the electricity and district heating sectors in a winter week in 2045* — Figure 13



Fraunhofer IEG based on Fraunhofer ISI et al. (2022b). * Early February 2045 in the T45-Electricity scenario. ** incl. electricity demand from large-scale heat pumps

In summer, flexible large-scale heat pumps together with heat storage systems will in future meet most of the heat demand. The feed-in and demand load curves in the electricity and district heating sectors for a typical summer week in 2045 under the scenario T45-Electricity are shown in Figure 14. This shows that large-scale heat pumps will (have to) be used extensively in the future, even in the summer when heat demand is low, and in particular whenever electricity generation from solar and wind power plants is particularly high.

This flexible, "green electricity-led" operation of heat pumps reduces the load on the electricity grids through coupling with the heating sector, avoids unnecessary curtailments on renewable electricity production and reduces the carbon footprint of heat generation. However, the majority of the heat generated during these periods is not consumed immediately, but is saved in heat storage facilities for periods when higher heat demand coincides with low renewable electricity supply.

The resulting heat storage capacity requirements in the T45 scenarios are shown in Figure 15. This shows that the total installed heat storage capacity has to increase from about 66 GWh in 2020 by a factor of 9-13 to reach 625-871 GWh in 2045. In the optimised energy system of the T45 scenarios, the large-scale heat storage facilities are designed to cover the maximum heat demand in 2045 for an average of 15 to 21 hours when fully loaded. Compared to 2020, this amounts to an increase in the discharge time by a factor of 6–9.

Seasonal thermal energy storage, such as underground geothermal storage, aquifer storage, mine or pit storage, or large borehole heat exchangers, was not explicitly considered in the long-term scenarios. This means that in individual district heating systems, heat storage can under certain conditions play a greater role.[6]

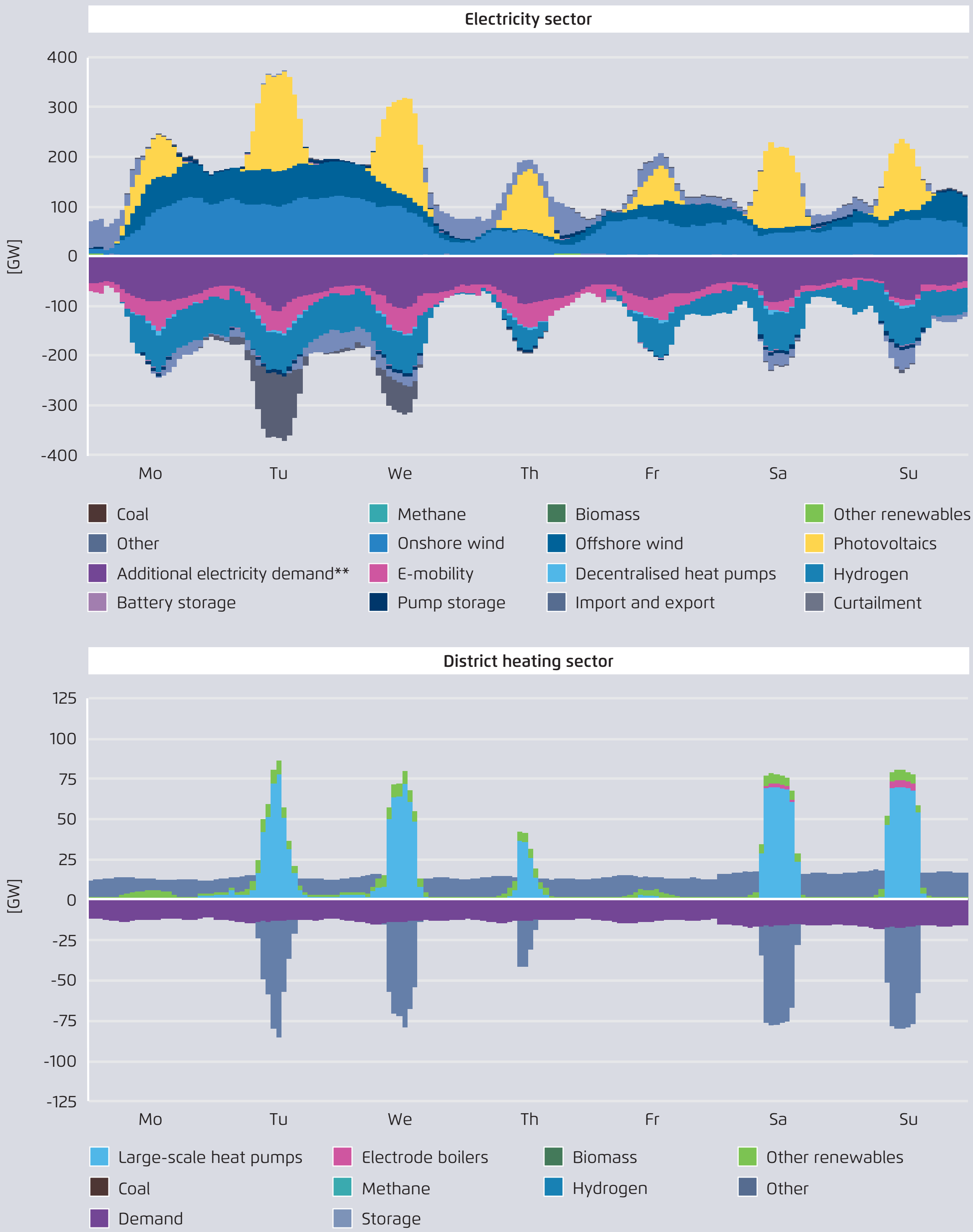
The flexible and system-supporting operation of large-scale heat pumps is ecologically and economically advantageous and enables the use of a high proportion of renewable energy. In an economically optimised mode of operation, the contribution of large-scale heat pumps to heat generation increases

- → as the share of wind and photovoltaics in electricity generation increases, because this equates to a lower CO_2 emission factor in the electricity mix;
- → as the residual load decreases, because the "electricity surpluses" from renewable energy sources acquire monetary value through the coupling of the sectors made possible by the heat pumps;
- → as electricity prices fall, because this reduces the electricity supply costs for heat pump operators.

This is clearly confirmed by the regression analyses on the relevant data from the T45-Electricity scenario shown in Figure 16. A prerequisite for this is an electricity market designed in such a way that the low electricity production costs from renewable energy sources also result in low electricity purchase costs for electricity consumers. In order to enable large-scale heat pumps to be operated flexibly in a way that supports the system, market price signals must not be distorted – as is the case, for example, with the existing network use charging system, which rewards steady and constant network use (high full load hours).

6 In addition to geological suitability and/or the space available for seasonal heat storage, high-quality heat sources (high COP or low operating costs) need to be available.

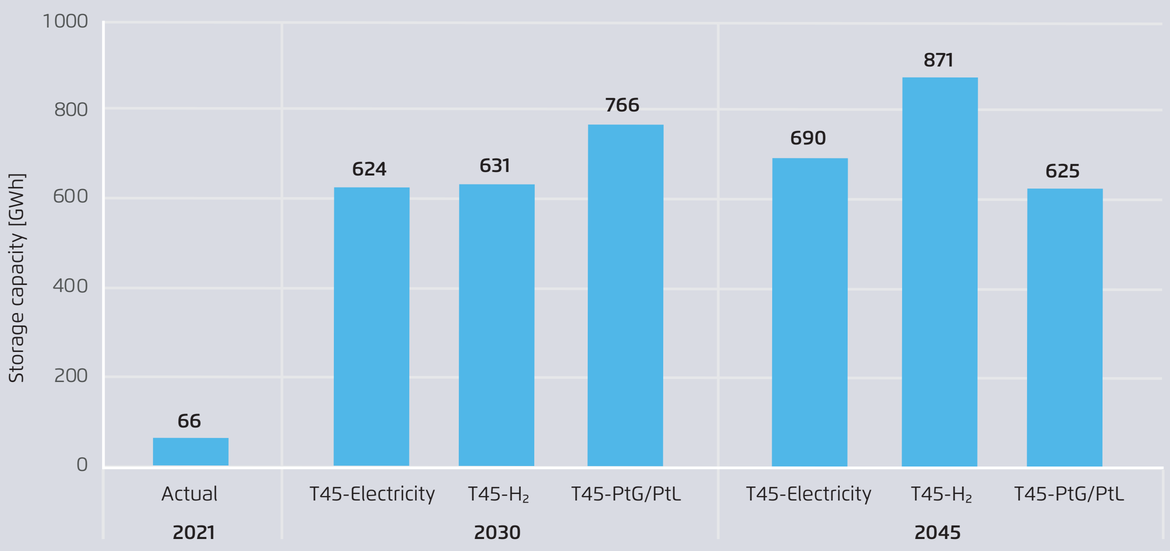
Operation of the electricity and district heating sectors in a summer week in 2045* Figure 14



Fraunhofer IEG based on Fraunhofer ISI et al. (2022b). * Late August 2045 in the T45-Electricity scenario. ** incl. electricity demand from large-scale heat pumps

Development of heat storage capacity in district heating

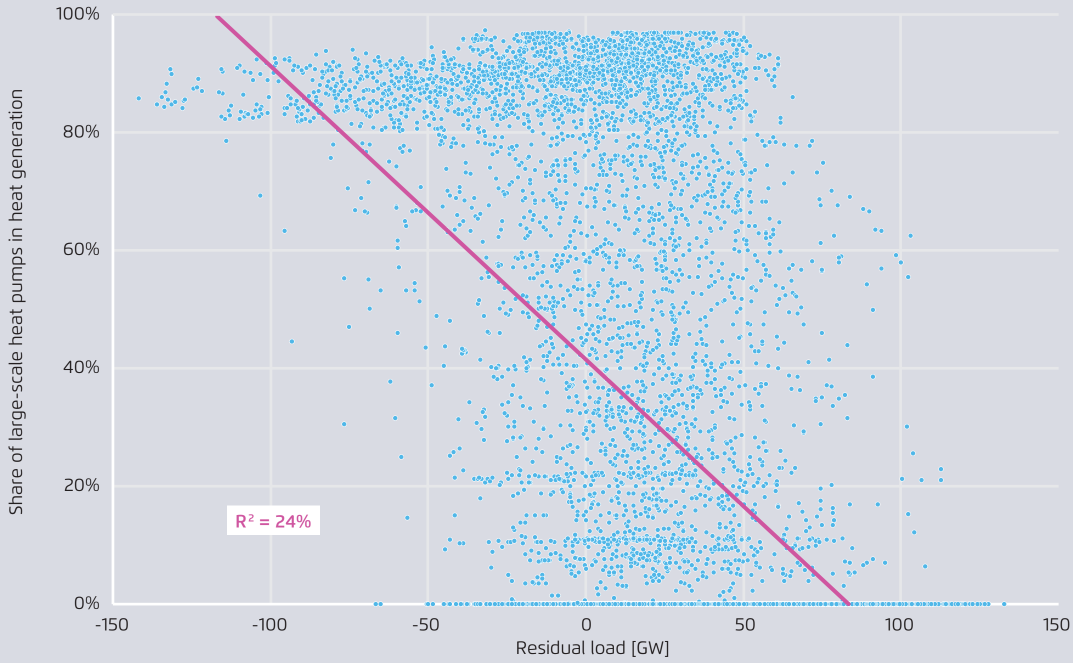
Figure 15



Fraunhofer IEG based on AGFW (2022), Fraunhofer ISI et al. (2022b)

Share of large-scale heat pumps in heat generation as a function of residual load

Figure 16



Fraunhofer IEG based on Fraunhofer ISI et al. (2022b)

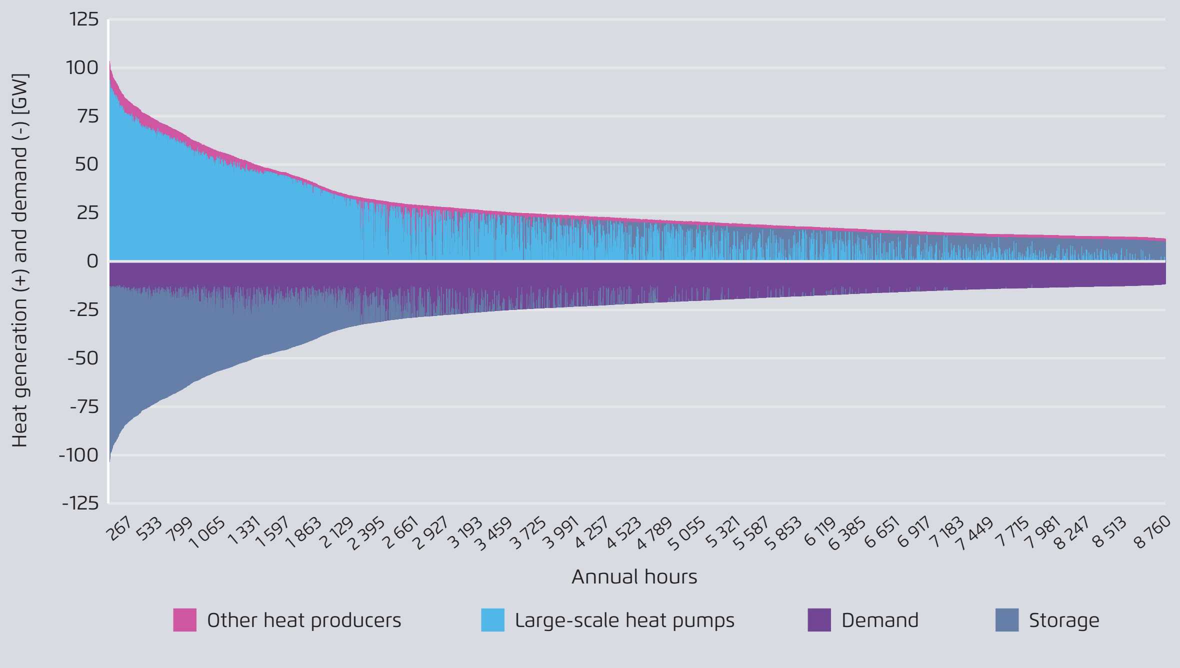
In future, large-scale heat pumps in district heating systems will be operated with an average of only around 1 300 full load hours per year. In order to be able to meet the high operating flexibility requirements, large-scale heat pumps will have to have greater excess capacity with respect to their designated heat output in the future. This means that the installed capacity of large-scale heat pumps will clearly exceed the maximum heating load of the customers connected to the district heating networks in the future. Consequently, the sum of the annual full load hours of large-scale heat pumps in the future will be significantly lower than today (around 1 247 flh in 2030 and around 1 308 flh in 2045 (in the T45-Electricity scenario, see Figure 17)).

The influence of the expected future rate of utilisation of a large-scale heat pump on its cost-effectiveness and the question of what effect different COPs (Coefficients of Performance),[7] different heat sources and different utilisation periods have on the heat production costs and thus on the cost-effectiveness of a large-scale heat pump project can be investigated during the initial evaluation phase already by means of sensitivity analyses. A selection of useful sensitivity analyses for providing rough guidelines is described in Chapter 7.2.

In contrast to district heating systems, production processes in industry usually have a significantly higher annual rate of utilisation. For the heat pumps used to supply these production processes with heat, an average of around 6 000 full load hours can therefore be assumed (Agora Industry and FutureCamp 2022).

7 The COP expresses the ratio of the thermal power generated to the electrical power used.

District heating load curve* in 2045 | Figure 17



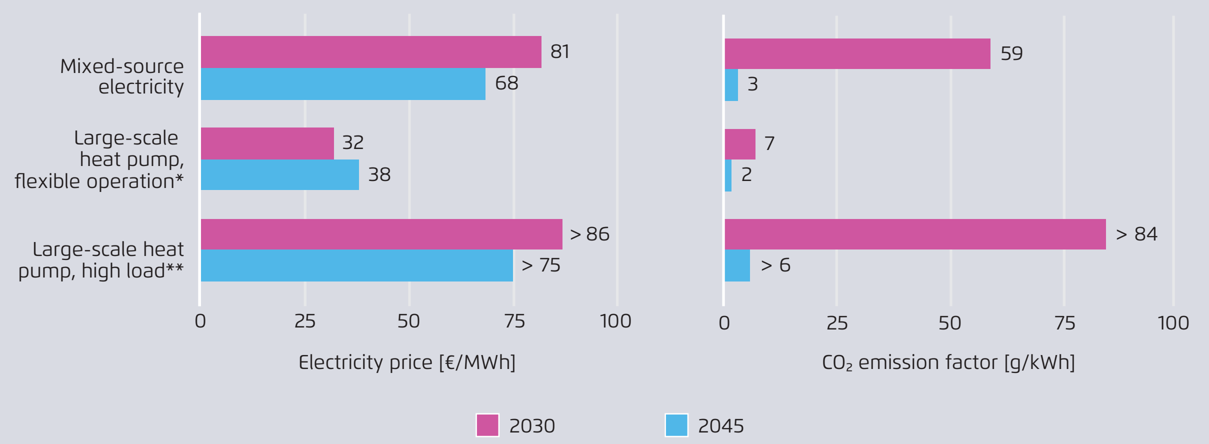
Fraunhofer IEG based on Fraunhofer ISI et al. (2022b). * Heat load incl. storage loading in the T45-Electricity scenario

Through "green power-led operation", large-scale heat pumps can very quickly achieve very low CO_2 emission factors. Operating large-scale heat pumps flexibly and geared to the wholesale electricity price increases the share of renewable energy in the electricity supply. The resulting electricity mix for use in heat pumps has a significantly lower CO_2 emission factor than the overall electricity mix for Germany (-88 percent in 2030 and -55 percent in 2045). This benefit of "green power-led" operation is particularly relevant in the phase up to about 2030, and it diminishes in inverse proportion to the increasing share of renewables in the overall electricity mix in Germany. The prerequisite for this, however, is that the electricity price signals do not continue to be distorted by a network use charging system that penalises flexible electricity procurement with high load peaks at times of high electricity supply and low full load hours.

Replacing CO_2-intensive fossil heat generation with large-scale heat pumps with a very low CO_2 emission factor in this way can quickly and substantially reduce CO_2 emissions in the district heating sector. Flexible operation of large-scale heat pumps (low number of full load hours) significantly reduces electricity supply costs on the wholesale market compared to continuous operation (high number of full load hours). In scenario T45-Electricity, this results in savings in electricity production using large-scale heat pumps of around 40 to 60 percent compared to the average annual price.

Figure 18 summarises, for the years 2030 and 2045, the minimum economic (electricity price) and environmental (CO_2 emission factor of the electricity) benefits from the flexible use of large-scale heat pumps compared to an intensive operating mode (high number of full load hours).

Minimum economic and ecological benefits*** of flexible operation of large-scale heat pumps — Figure 18



Fraunhofer IEG based on Fraunhofer ISI et al. (2022b) assuming a constant COP of 3.0 * Corresponds to the economically optimised operation of the T45-Electricity scenario with low full load hours. ** Heat generation from the large-scale heat pump matches immediate heat demand (no use of heat storage). The maximum heat generation of the large-scale heat pump is limited so that 6 000 full load hours occur over the year. Assuming that the hourly wholesale prices and CO_2 emission factors on the electricity market do not change as a result of the change in the operating mode of the large-scale heat pump. *** Electricity price and CO_2 emission factor for operation under high load apply only to the first marginal unit. With each additional unit that switches from flexible operation to high-load operation, the price of electricity (and the CO_2 emission factor) increases, because increasingly expensive (and CO_2-intensive) electricity generation plants are needed to meet the additional demand.

An overview of the other reference years and the T45-H_2 scenario can be found in Appendix A.2.

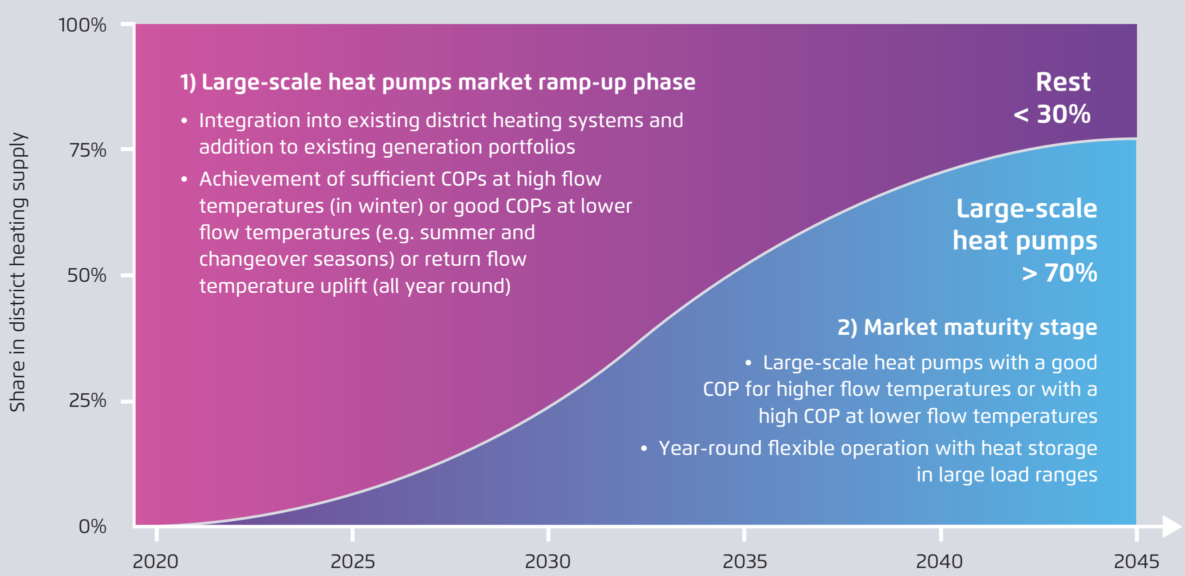
The requirements described above for the highly flexible operation of large-scale heat pumps mean that in the future they must be technically capable of covering very large output ranges with high load gradients – either as a stand-alone system or in combination with other large-scale heat pumps of different output classes and operating characteristics. Both the current technological state of the art and foreseeable technical progress as well as the statements of manufacturers and planning bodies specialising in large-scale heat pumps indicate that this is feasible (for more information, see Chapters 5 and 6).

3.3 Key data on the required roll-out of large-scale heat pumps in district heating

In order for large-scale heat pumps to cover a minimum of 70 percent of the district heating demand by 2045, several gigawatts of heat output and several gigawatt hours of heat storage capacity will have to be added every year starting from now. This planned roll-out of large-scale heat pumps can be roughly divided into two phases (see Figure 19):

→ In the first phase of the market ramp-up, large-scale heat pumps will still mainly be integrated into existing district heating systems with high flow temperatures and will supplement existing generation portfolios. In addition, especially at the neighbourhood and municipal district levels, new district heating systems operating at lower

Roll-out of large-scale heat pumps in two overlapping phases | Figure 19



Fraunhofer IEG (2023)

temperature levels will be created, powered by large-scale heat pumps. This phase is characterised by high flow temperatures (in winter) or good COP values (see Chapters 4 and 5) at lower flow temperatures (for example in the summer and change-over seasons) or when large-scale heat pumps are integrated into the return flow of existing heating systems (all year round).

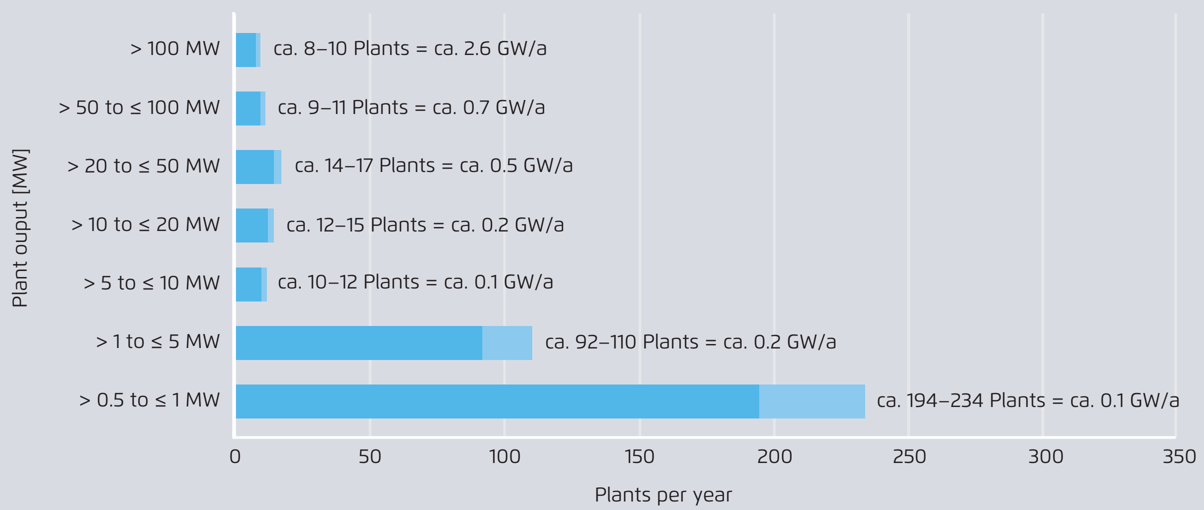
→ In the second phase of market development, large-scale heat pumps will take on the main role in heat supply in more and more district heating systems and, in combination with large-scale heat storage systems, will be operated flexibly and in a way that supports the overall system all year round. Technological progress is leading to improved COP values both in modern networks with low flow temperatures and in the remaining networks with higher flow temperatures.

Around 340 to 410 large-scale heat pump projects with a combined capacity of 4.0–4.9 GW need to be added every year. As already described in Chapter 3.1, the T45 scenarios indicate an economically optimal output from large-scale heat pumps of 90 GW to 108 GW in 2045. With less than 1 GW of large-scale heat pump capacity installed in Germany in 2023, this corresponds to an average annual expansion requirement of around 4.0–4.9 GW per year in the remaining 22 years until 2045.

Assuming the size distribution of large-scale heat pumps is in line with the CHP plant stock above 500 kW (see Figure 20), this would equate to around 340 to 410 individual new projects per year, all of which would have to go through the entire planning, approval and financing process and require the corresponding resources.

A comparison with the other major climate neutrality studies shows that large-scale heat pumps will cover a large part of future district heating generation in almost all scenarios. The precise proportion depends primarily on the extent to which the potential input from the utilisation of waste heat,

Distribution of the annual large-scale heat pump addition of 4.0 to 4.9 GW among the different output classes based on the current CHP plant stock* — Figure 20



Fraunhofer IEG based on Fraunhofer ISI et al. (2022b), BNetzA (2023a). * Assumption: size distribution of large-scale heat pumps corresponds to that of CHP plants > 500 kW at the end of 2022.

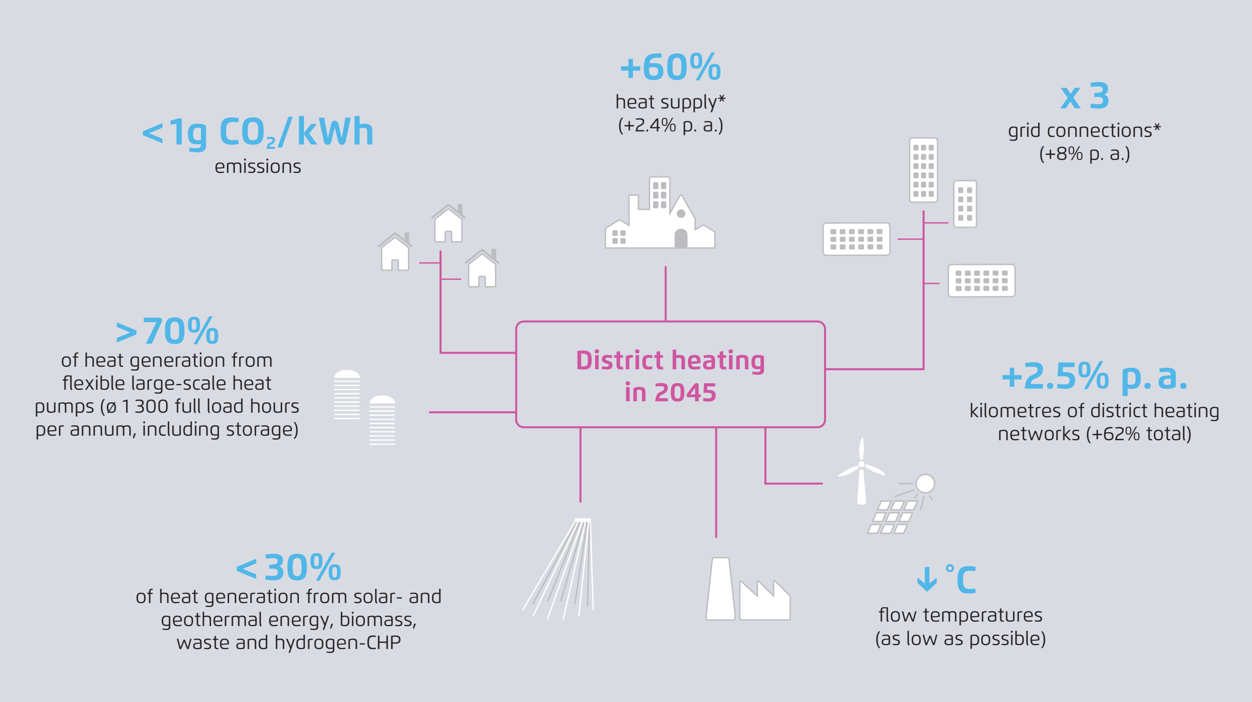
geothermal energy and solar thermal energy is included in the scenarios, as well as the pace of the renovation of the building stock.

However, there is no doubt that the future expansion path for large-scale heat pumps must be extended and that the appropriate political guidelines and regulatory frameworks must be in place for this to happen.

To put this into perspective: an average expansion target of 4.5 GW for new large-scale heat pump capacity per year would correspond to an investment/market volume of around 2.7–3.6 billion euros per year, assuming unit investment costs (incl. planning, heat storage, peripherals, construction and commissioning) of 600-800 euros per kW. More detailed information on the breakdown and level of unit investment costs for each thermal output class and heat source can be found in Chapter 7.2.

The typical district heating system in 2045 will be significantly different from those of 2020. Figure 21 provides a simplified overview of how the typical German district heating system would have to change compared to the year 2020 if the results of the T45 scenarios are used as a starting point and transferred from the national to the local level.

The typical district heating system of a German city in 2045* — Figure 21



Fraunhofer IEG based on Fraunhofer ISI et al. (2022); * compared to 2020; numbers based on the long-term scenarios III (Fraunhofer ISI et al. 2022b).

4 Heat sources: potentials and preconditions

4.1 The importance of the heat source for large-scale heat pumps

In the preceding chapters, the significance of large-scale heat pumps for the success of the heat transition and the energy transition as a whole was examined. It was shown that, from an energy industry perspective, a very large number of large-scale heat pumps must be planned, installed and operated in a system-supporting manner very quickly in order for district heating systems to be efficiently decarbonised.

This chapter will analyse the different heat sources available in Germany and their potential advantages and disadvantages with regard to both their exploitation and use as well as the design and operation of large-scale heat pumps.

Heat pumps take environmental or waste heat from a given heat source at a low temperature and release it, with the addition of the operating energy required, to a heat sink at a higher temperature. The properties of the heat source and the heat sink determine each project and have an influence on its economic performance.

The most important environmental and waste heat sources for the operation of large-scale heat pumps are evaluated in Table 1 according to their most important features. These will be explained in detail in the following subchapters. This list could be extended further: other heat sources include, for example, solar thermal energy and the thermal use of underground railway shafts in metropolitan areas.

On the sink side, there are approximately 3 800 individual district heating networks in Germany – i.e. heat sinks – with varying network temperatures, network densities and pipeline lengths (see Chapter 2.4). It is expected that the number of district heating

Characteristics and relative evaluation* of various environmental and waste heat sources for the operation of large-scale heat pumps — Table 1

Environmental and waste heat sources	COP	Investment costs	Seasonal availability	Temperature	Potential
Ambient air	––	+	–	-10–30 °C	unlimited
Near-surface geothermal energy	+	o	+	5–15 °C	450 TWh/year
Medium-deep and deep geothermal energy	+	––	+	15 °C (no upper limit)	300 TWh/year
Mine water	+	o	+	10–40 °C	4 TWh/year**
Thermal energy from water bodies (rivers, lakes, seas)	o	+	o	4–25 °C	86 TWh/year***
Waste water and sewage treatment plants	+	+	+	10–17 °C	34 TWh/year
Industrial waste heat	+	+	+	20–100 °C	52 TWh/year****
Waste heat from data centres	+	+	+	20–60 °C	16 TWh/year

Fraunhofer IEG based on Born et al. (2022), Bracke et al. (2022), Bracke et al. (2018), Kammer (2018), Gerhardt et al. (2019), Wolf (2017), Fritz und Pehnt (2018), (AGFW) (2020). * Evaluation of individual factors relative to the other listed environmental and waste heat sources. ** Significantly lower following the end of opencast lignite mining. *** No studies known on thermal use of seawater. **** Calculation derived from technical potential and assumed COP of 2.5

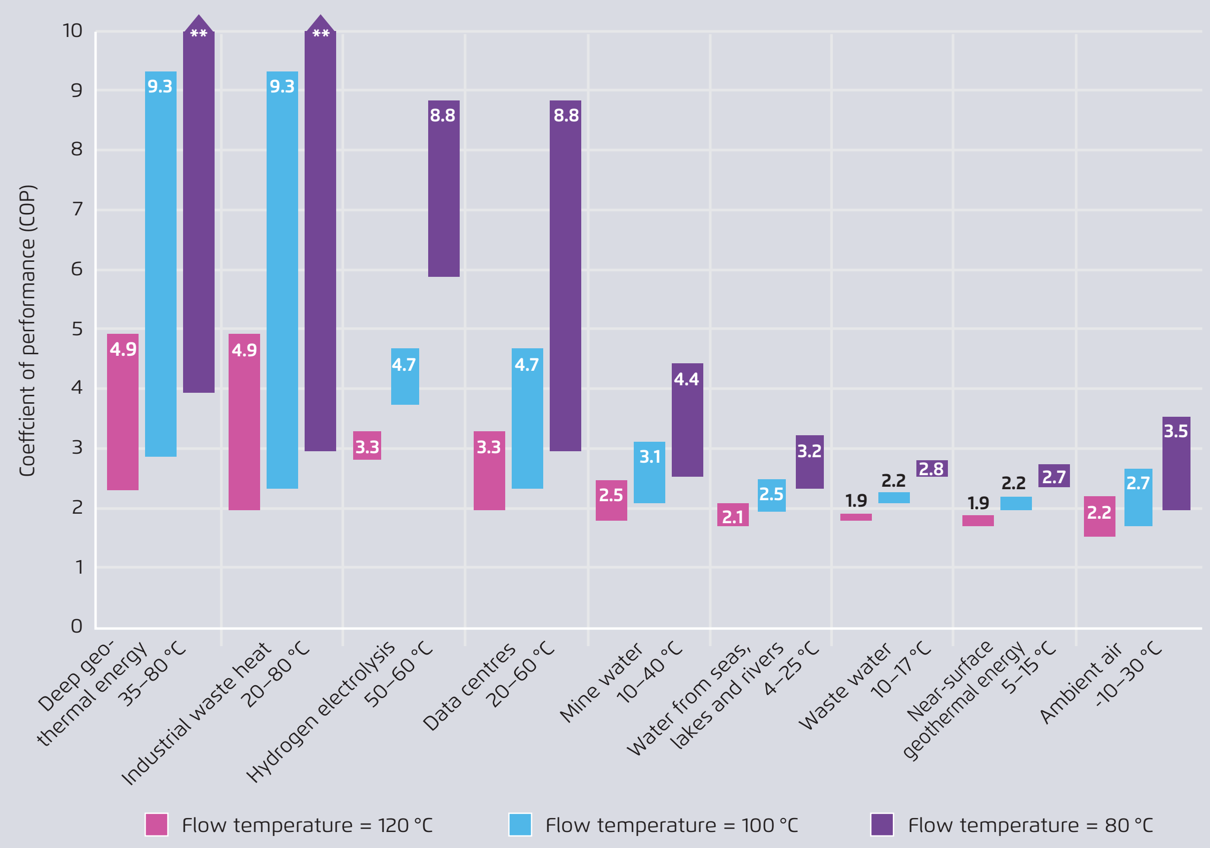
systems and thus the total pipeline length will continue to grow (see Chapter 3.1).

The efficiency of a heat pump increases with higher source and lower network temperatures. In addition to differences in the temperature at which heat is taken in by a heat pump, environmental or waste heat sources also differ in terms of how difficult it is to make them usable. The efficiency of a heat pump increases as the temperature of the heat source rises, which reduces the operational expenditure (OPEX). The resources required to tap the environmental or waste heat and connect it to the heat pump have a considerable influence on the capital expenditure (CAPEX).

The specific site conditions with regard to the temperature of the heat source and of the district heating network determine the level of system efficiency that can be expected. The preconditions for the efficient operation of large-scale heat pumps therefore vary from location to location and from project to project.

Theoretically possible COPs of heat pumps according to heat source and network flow temperature, assuming an effciency rating* of 50% and different flow temperatures of the district heating network

Figure 22



Fraunhofer IEG (2023). * The highest theoretical COP of a heat pump is measured using the so-called Carnot process. It can be used as a reference model for a hypothetical heat pump operating without losses. The ratio of real COP to Carnot COP is referred to as the effciency rating. Due to various influencing factors, such as friction in the system or radiated heat, effciency ratings are generally at around 40 to 60 percent at present. ** When the source temperature approaches the flow temperature, the COP converges towards infinity.

Figure 22 shows the theoretically achievable COPs for combinations of different heat sources and heating networks.

A number of regulatory requirements must be taken into account for the exploitation of the various heat sources. Large-scale heat pumps are usually marketed by the manufacturer as a single unit complete with the necessary safety approvals. The peripheral elements for the system as a whole require separate approval because they are usually not provided by the manufacturer of the unit. The construction of a complete system with a connection to both the heat source and the heat sink entails new regulatory approval requirements for the potential operator of the system. A number of technical specifications for large-scale heat pumps are involved, irrespective of the heat source. The most important of these are described below.

For building authorisation to be granted, the provisions of the local building regulations and in particular DIN EN 378 1 to 4 (Refrigeration systems and heat pumps – Safety and environmental requirements) must be met. The DIN EN 378 standard specifies the recognised state of the art for the safe installation of refrigeration equipment and heat pumps and regulates, for example, the fire safety requirements.

Large-scale heat pumps do not automatically require authorisation under the Federal Immission Protection Act (Bundesimmissionsschutzgesetz, BImSchG). The refrigerant quantities in large-scale systems commonly used today are well below the thresholds that would necessitate a permit. For plants in the three-digit MW range, this would have to be checked for the refrigerant ammonia, for example.

With regard to immissions, however, heat pumps are certainly subject to the administrative provisions of the Federal Immission Protection Act (Technical Instructions on Noise Protection – Technische Anleitung zum Schutz gegen Lärm, or TA-Lärm for short). Together with the Industrial Safety Regulation (Betriebssicherheitsverordnung, or BetrSichV), which regulates many other safety aspects such as the operation of high-pressure equipment, and the Workplaces Ordinance (Arbeitsstättenverordnung, or ArbStättV), this gives rise to requirements for sound level reductions at defined distances from the heat pump.

The installation of heat pumps affects water – a protected resource regulated by the Water Resources Act (Wasserhaushaltsgesetz, WHG) and the State Water Acts (Landeswassergesetze, LWG) – not only in the case of thermal energy from water bodies, but in almost all cases, because peripheral circuits often use antifreeze agents that pollute water. Authorisation under the relevant water legislation is then required.

It should be noted that in Germany, the state and even local authorities are responsible for permits and approvals, and they have different levels of experience with regard to large-scale heat pump projects.

In the following section, the challenges posed by accessing the different heat sources, which have only been listed in brief so far, will be addressed in more detail. This includes not only the technological constraints but also the current legal situation in Germany regarding the regulatory requirements for large-scale heat pumps including peripherals.

4.2 Potentials and preconditions of different heat sources

Ambient air – an inexhaustible heat source, but with disadvantages in the cold season

Ambient air, which is widely used for smaller decentralised heat pumps, is available everywhere. This heat source is subject to strong seasonal temperature fluctuations and to low temperatures during the heating season. These low temperatures pose a challenge in several respects. Large temperature differences to the outside air, especially in district heating systems with high flow temperatures, can require adapted operating modes in individual cases, such as an increase in return flow in winter or operation that is limited to the changeover seasons.

The use of air as a heat source requires comparatively little investment compared to other heat sources, but it has disadvantages with respect to operating and electricity procurement costs due to the lower annual performance factors that can be achieved.

For large-scale heat pumps using air as the heat source, very large volume flows must be moved through the fans. Although heat pump units can be installed in sound-insulated buildings, this is not possible for air heat exchangers and the fans they use. Therefore, when choosing locations, it has to be ensured that the immission guidelines stipulated by TA-Lärm are adhered to – just as with conventional CHP plants. The cooling of humid air can lead to a build-up of ice on the heat exchangers of an air source heat pump, which then have to be defrosted. Defrosting processes, including when heat pumps are started, require additional energy input, which further reduces the system efficiency.

The cooling of the source air can have a positive effect on the climate, especially in urban areas. However, careful planning is needed to guide the air flows appropriately within the given geographical parameters. This is because cold air rises more slowly than warm air and there is a risk of cold air lakes or ice forming under certain conditions.

Near-surface geothermal energy – could potentially provide up to 75 percent of the heat required in Germany for space heating and hot water

Near-surface geothermal energy is the term used for energy at depths of up to 400 metres. Geothermal energy is a so-called freely-mineable resource, the ownership of which is not tied to a plot of land. However, there are exceptions if the geothermal use is directly linked to the land. The commercial extraction of geothermal energy therefore requires a mining authorisation from a state mining office. Geothermal energy also affects water, a protected resource, in a particular way. According to the Water Resources Act (Wasserhaushaltsgesetz, WHG) and the State Water Acts, contamination of the groundwater or any other adverse change in its properties must be avoided. In terms of both water legislation and technology, a distinction is made between borehole heat exchangers and boreholes for groundwater use. Geothermal probes are closed systems that do not directly use water. Nevertheless, authorisation under water legislation may be required, as water-polluting antifreeze is almost always passed through the circuits, which in the event of a leak could lead to water contamination. Open systems for groundwater use are in principle subject to strict regulation.

Geothermal energy is an environmental heat source which is available all year round at stable temperatures. Shallow collectors can be installed directly below the earth's surface. Because their performance increases considerably when spread over a larger area, collector systems of this kind are not very suitable for large-scale heat pumps. Agrothermic projects in rural areas could prove to be an exception here. In general, boreholes for open or closed systems are more promising. In the roadmap "Near-surface geothermal energy" published by Fraunhofer IEG in 2022, a potential supply of useful heat of around 496 to 600 TWh per year was estimated for Germany at an average COP of 4, which amounts to up to 75 percent of the heat required in Germany for space heating and hot water (Born et al. 2022).

The overall efficiency of the plant is determined jointly by the mode of operation, the geometry of the extraction systems and the properties of the subsurface. As these are tried-and-tested standard technologies and the near-surface subsurface has generally been well explored, the planning and development risk can be classified as low, which is not the case with medium-deep and deep geothermal energy.

Medium-deep and deep geothermal energy – great potential, and high source temperatures available all year round, but costly to exploit and not available everywhere

As the drilling depth increases, we speak of medium-deep and deep geothermal energy, although the demarcation between the two (approx. 1 000–1 500 m) is not uniform in the literature. Beyond drilling depths of about 600–800 m, small mobile drilling rigs can no longer be used. This results in a steep increase in development cost. With increasing depth, the temperature in Central Europe rises by about 3 kelvins per 100 m. If the hydraulic permeability of the rock formations is sufficient, deep geothermal boreholes can provide heat at high temperature levels. The total potential of the South German Molasse Basin, the Upper Rhine Graben, the North German Basin and the Rhine-Ruhr region is estimated to be between 150 and 300 TWh per year at temperatures of 35 to 65 °C (Bracke et al. 2022). Exploration activities, the drilling of deep boreholes and the subsequent extraction of medium-deep and deep geothermal energy are all subject to mining legislation.

Medium-deep and deep open geothermal systems are subject to a high exploration risk. For example, the quality of the reservoir may not meet expectations with regard to the temperature or the hydrochemical properties of the thermal water. Above all, however, production rates that fall short of expectations can lead to higher operating costs over the lifetime of the system. It is possible to increase the natural permeability by hydraulic stimulation, if necessary in combination with acidification. Diversion drilling or lateral drilling are also possible within the working lifetime. However, such methods involve considerable additional investment as well as risks with regard to licensing regulations. Deep geothermal energy is therefore characterised by relatively high development costs (see Chapter 7.2).

In many countries, state actors assume the exploration risk. Increasingly, however, private insurance models are coming to the fore. A purely private-sector scheme for covering the exploration risk was devised and applied for the first time in 2003 in the geothermal project in Unterhaching near Munich (Seipp et al. 2016). In addition to insurance, grant, loan or guarantee schemes are also conceivable. Particularly with regard to deep geothermal energy, Germany is under-researched. In October 2021, the Federal Environment Agency (Umweltbundesamt, UBA) therefore invited tenders for carrying out a study on the “Expansion of climate-neutral renewable district heating from deep geothermal sources”. The objectives of this study include developing ways to improve the availability of data for the exploration and execution of geothermal projects as well as devising different funding instruments to safeguard against exploration risks (Bracke et al. 2022).

Pit water – only available in a limited number of locations, but a very valuable local heat source

It is not only through geothermal boreholes that heat can be extracted from the earth. The extensive mining of hard coal, mainly carried out in North Rhine-Westphalia, has led to subsidence of the ground above the former mine shafts. To prevent further subsidence and to protect against flooding, the water in the coal mines must be continuously pumped out. This dewatering thus represents a so-called perpetual burden. The use of sump water from opencast lignite mining, on the other hand, is limited to the duration of the mining operation. Taking all sites into account gives a potential of about 4 TWh per year for the year 2035 and 1 TWh per year in 2050 at an average source temperature of about 35 °C (Bracke et al. 2018).

Thermal energy from surface water bodies – an easily accessible energy source with strong seasonal temperature fluctuations

The term “thermal energy from water bodies” encompasses the energetic use of environmental heat from all surface water bodies such as lakes, rivers and seawater. In principle, this requires authorisation under the legislation pertaining to water. The cooling of overheated bodies of water can to a certain extent have positive effects on their ecology or on the urban climate. In general, restrictions are imposed to limit the degree of cooling permitted or the maximum amount of water that can be discharged. Since large-scale heat pumps only cool the water and do not alter it materially, there is no danger that its use as a heat source will lead to competition with other potential uses.

Unlike in other countries, such as Switzerland or the UK, there is not yet a national registry for water heat sources in Germany. In Switzerland, a register of this kind was compiled for lakes and rivers by the Swiss Federal Institute of Aquatic Science and Technology (Eidgenössische Anstalt für Wasserversorgung, Abwasserreinigung und Gewässerschutz, Eawag) (Gaudard et al. 2018). While, as far as the authors are aware, there are still no studies at all on the potential for thermal use of seawater in Germany, for the potential from lakes there is only a rough estimate based on the heat demand in their immediate vicinity. This found a potential extraction capacity of around 59 TWh per year (Kammer 2018). Temperatures vary greatly according to the season and are around 4 to 25 °C (Gerhardt et al. 2019).[8]

From a technological point of view, the biology of the water bodies also poses special challenges. To avoid fouling, for example by mussels, high flow velocities and rakes and/or filters are needed. Heat exchangers which are easy to clean, such as shell-and-tube heat exchangers, must be used, and it must be ensured that the piping system can be cleaned internally, which means that more space is required. In addition, attempts are being made in practice to meet water protection requirements by using less hazardous refrigerants. Of particular interest here is the non-flammable and non-toxic refrigerant CO_2. This requires very high pressures in the heat pump, which makes it more expensive. In addition, its thermodynamic properties require particularly low return temperatures to ensure efficient operation. The reasons for this are explained in more detail in Chapter 5.

Wastewater and sewage treatment plants – available all year round and in almost all larger urban areas, i.e. close to heat sinks

Sewers and wastewater treatment/sewage treatment plants represent an almost universally available heat source with low temperature fluctuations between about 17-20 °C in summer and 10-12 °C in winter (AGFW 2020). The COP in winter is therefore usually better than with air or water bodies as heat sources. In addition, this heat source is often close to the heat consumers (Ecke and Göke 2017).

Theoretically, with the total amount of wastewater and sewage water available throughout Germany, around 31 TWh of environmental heat can be extracted annually with a temperature draw-off of 3 kelvins. The extraction capacity is limited by the minimum wastewater temperature required at the sewage treatment plant inlet. However, because the flow rates vary over time and because only part of the potential can be technically exploited, the theoretical potentials documented in the literature will be lower in practice. Already completed projects and studies have shown that a temperature reduction of 4 kelvins does not impair the functioning of sewage treatment plants (Fritz and Pehnt 2018).

For sewers, a potential of around 25 TWh per year was calculated for a temperature reduction of 4 kelvins (Fritz and Pehnt 2018) and for a temperature reduction to 3 °C a potential of around 8-9 TWh per year (Gerhardt et al. 2019) for wastewater treatment plants.

8 The lower limit equates to the source temperature required to avoid icing on the source side due to cooling. It corresponds to the temperature at which water can be pumped from only superficially frozen surface water bodies in winter due to the anomalies associated with water at 4 °C.

One technical challenge posed by the use of sewers is the highly fluctuating water supply.[9] In addition, contamination by biological matter poses a problem for the use of sewers and wastewater treatment plants. Particularly in the case of sewage treatment plants, care must be taken to protect the clean water from refrigerant pollution. Even stricter requirements apply here than for thermal energy from water bodies. This can be addressed in indirect integration by means of intermediate circuits and in direct integration using double-walled heat exchangers.

In the event of contamination of clean water, not only technical solutions are required, but also a legal clarification of liability, and thus close cooperation is needed from the very beginning between sewage treatment plant operators and wastewater companies and the operators of large-scale heat pumps.

Industrial waste heat – great potential, very close cooperation needed between the supplier and the user of the waste heat

Industrial waste heat is produced throughout Germany in large quantities and at different temperature levels, sometimes above the temperature level of district heating networks. Especially at higher temperatures, industrial waste heat should first and foremost be fed back into industrial processes as much as possible in order to exploit the potential for increasing energy efficiency there. Only after this utilisation cascade, or where no heat recovery is possible or justifiable from an energy or economic point of view, should the remaining industrial waste heat be extracted for use in district heating networks. The total potential, excluding the energy required to drive the large-scale heat pumps, is estimated at 86 TWh per year just for the temperature range < 100 °C (Wolf 2017).

9 In 2019, 26 percent of the wastewater volume generated in Germany was accounted for by periodically occurring rainwater. A further 17 percent is accounted for by infiltration (UBA 2023b). This could also be assumed to be periodic.

However, when heat is recovered from industrial processes, the heat is only a by-product. This means that industrial companies will not align their production processes with heat requirements and that any heat recovery must not have any adverse effects on the main process. The resulting requirements for the maintenance of temperature differences and material flows can mean additional buffer storage needs, for example in batch processes. Contamination must also be avoided – as with thermal energy from water bodies or heat recovery from sewage water.

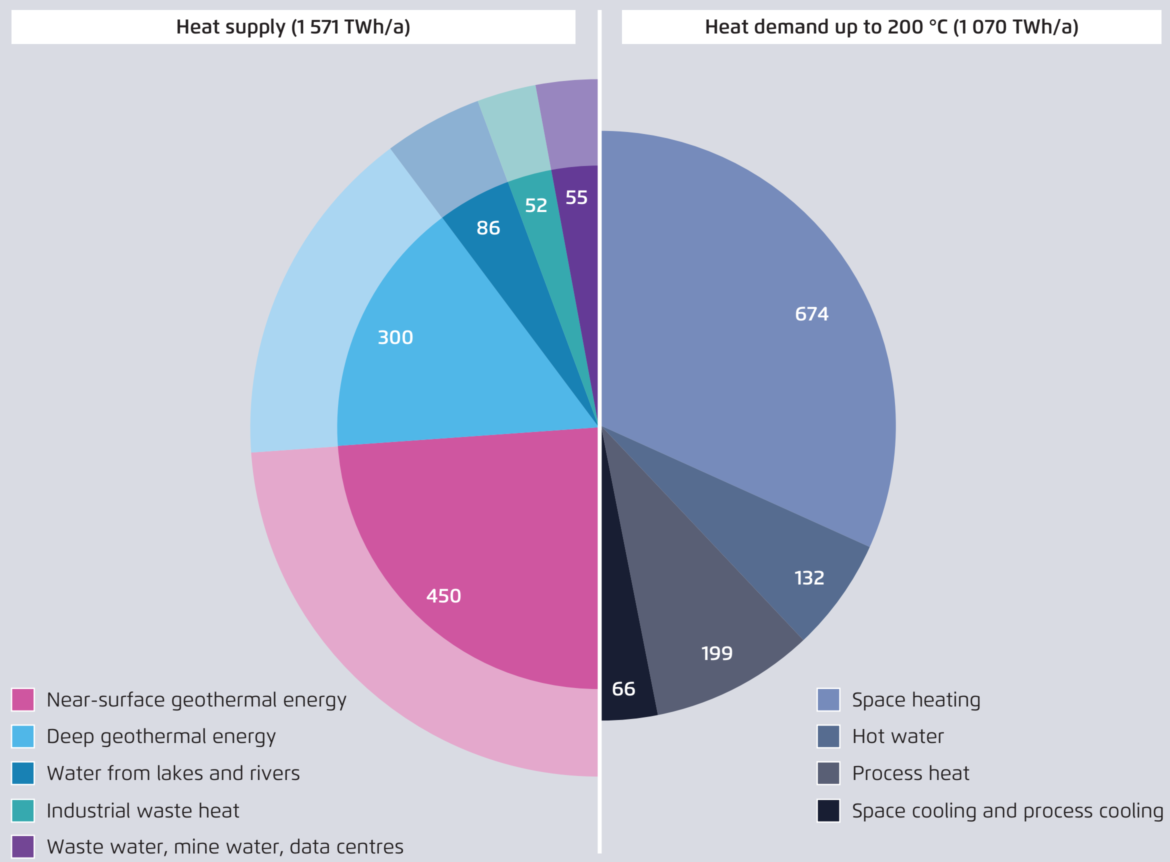
In addition, there is considerable need for coordination between the heat consumers and the industrial companies, which have different (typically shorter) investment and operating horizons from those of a district heating network operator. Cases are conceivable where the waste heat source could run out earlier than planned because industrial processes are altered or discontinued for business reasons. It is also possible that industrial transformation could lead to restructuring of industrial sites and thus to a reduction in the available waste heat. There is therefore a greater need for cooperation between the waste heat supplier and the waste heat user. Finally, the sale of waste heat must not lead to a fossil fuel "lock in".

Waste heat from data centres – great potential for synergies, provided the data centres are built close to the heat sinks

Due to advancing digitalisation, data centres will become increasingly important as waste heat sources. Even if decreasing electricity demand from data centres over time due to efficiency improvements is taken into account, a general increase in energy demand from this sector in Germany can be assumed due to numerous projects in planning or already announced. According to T45 long-term scenarios, demand is forecast to be around 16 TWh in 2025 and up to 23 TWh in 2045. The electrical energy used is converted into heat and can thus be made usable for heat pumps. Assuming a utilisation rate of 70 percent for the waste heat, this results in a maximum thermal potential of 16 TWh in 2045. In order for this potential to be realised, future data centres must be located close to heat sinks – for example, to a district heating system. The Energy Efficiency Act (Energieeffizienzgesetz, EnEfG, as of 19 April 2023) passed by the Cabinet stipulates, among other things, that data centres must cover their energy needs exclusively with unsubsidised electricity from renewable energy sources from 2027 onwards (and to at least 50 percent from 2024 onwards). New data centres starting their operations from July 2026 must also have a so-called energy consumption efficiency of at least 1.3 (data centres already in operation then must achieve this level by July 2030).

The temperature of the waste heat varies from data centre to data centre depending on the cooling system used. Whereas an air-cooled data centre generates temperatures of up to approx. 30 °C, the waste heat of a liquid-cooled centre is at around 60 °C.

Comparison of the potential heat supply* via heat pumps and the heat demand up to 200 °C** in Germany (excluding ambient air) — Figure 23



Fraunhofer IEG based on Born et al. (2022), Bracke et al. (2022), Kammer (2018), Gerhardt et al. (2019), Fritz und Pehnt (2018), Wolf (2017), Stobbe et al. (2015). * The heat supply is made up of the potential supply from different heat sources (darker colours) plus the necessary operating power (lighter colours) for the heat pumps, assuming an average COP of 2.5. ** Heat demand based on final energy consumption in Germany in 2021, excluding process heat of private households and process heat > 200 °C.

4.3 Potential of heat sources in Germany

Germany's heat requirements up to 200 °C could be completely supplied by heat pumps. Figure 23 shows the upper limits of the potential heat supply calculated so far for Germany for the heat sources discussed above (excluding ambient air) and compares them to the final energy consumption in the heating sector in 2021 as a reference point. There are still uncertainties regarding the potentials as described, which are reflected in the wide variations in the data available in the literature. However, several analyses of these potentials are currently being carried out or are planned, both at the federal level and in several federal states – not least in order to lay the necessary groundwork for numerous heat transformation studies and local heat plans which will have to be drawn up in the next few years. As a result, the data available for this area will improve in the next few years.

The heat demands summarised under the term process heat demands in Figure 23 are divided into different temperature and industry segments. They cover demands at temperatures of up to 200 °C and which could therefore be decarbonised effectively through the use of large-scale heat pumps. Up to these temperatures, as shown in Chapter 6.1 and Appendix A.3, serial production models from several large heat pump manufacturers are already available or in an advanced stage of development. In addition, some systems currently in development can reach sink temperatures of up to 250 °C. Above this temperature, other technologies using direct electricity can be used, such as electrode boilers or electric furnaces. Overall, about 37 percent of industrial heat demand is below 200 °C (UBA 2017).

5 Technological state of the art: main components, key data, potential for development

The choice of the most appropriate large-scale heat pump for any specific project is determined by the local operating conditions and parameters. They determine the design and the choice of refrigerant. The low source temperature defines the temperature at which locally available environmental heat can be taken up by the heat pump. The high sink temperature determines the temperature at which the heat to be provided by the large-scale heat pumps is supplied to a district heating network or an industrial process. If the parameters of the source and sink to be connected are known, an appropriate heat pump can be selected for the project.

5.1 Functional principle of compression heat pumps

Although large-scale heat pumps function according to the same thermodynamic principle as the more familiar small heat pumps for buildings, they are more like combined heat and power (CHP) plants in terms of their dimensions (heating capacity, volume flow, pressure ratios, space requirements), their complexity, the investment costs and the costs of operating, maintaining and servicing them.

The underlying technical principles are explained below using the example of the compression heat pump, which is the most common heat pump technology in district heating applications.

Closed-cycle compression heat pumps take up thermal energy at a low temperature and release it together with the drive power at a higher temperature to a heat sink. In the process, a refrigerant circulates inside and goes through four principal process steps: temperature increase through compression, heat transmission, expansion and warming.

In terms of components, the temperature increase occurs through the pressure increase in a compressor. In the simplest conceivable circuit for a closed-loop compression heat pump, heat is released via a first heat exchanger, expansion occurs via an expansion valve and heat is transferred via a second heat exchanger before the refrigerant is returned to the compressor.

In the heat exchangers, so-called phase changes take place during subcritical processes.[10] This is why the heat exchanger for the heat release from the refrigerant is called a condenser and the heat exchanger for the heat intake is called an evaporator. In transcritical processes, the heat transmission takes place without phase transition, which is why in this case it is called a gas cooler instead of a condenser. For the two heat exchangers, shell-and-tube heat exchangers are most common, and plate heat exchangers for less polluted media (Arpagaus 2019). Figure 24 is a schematic representation of a circuit with the four main components.

In order to increase the efficiency of compression heat pumps and for optimal system operation, a large number of different configurations have established themselves on the market. Figure 25 shows an example of the impact of selected configurations on the costs of the circuit components and on the COP for a heat pump process with fixed temperature lift and sink temperature values (Mateu-Royo et al. 2021).

Complex configurations with a larger number of components to increase the COP lead to higher investment costs. For this reason, it is always

10 Phase changes refer to changes in the aggregate state of media, i.e. transitions to a solid, liquid or gaseous state, for example through evaporation or condensation.

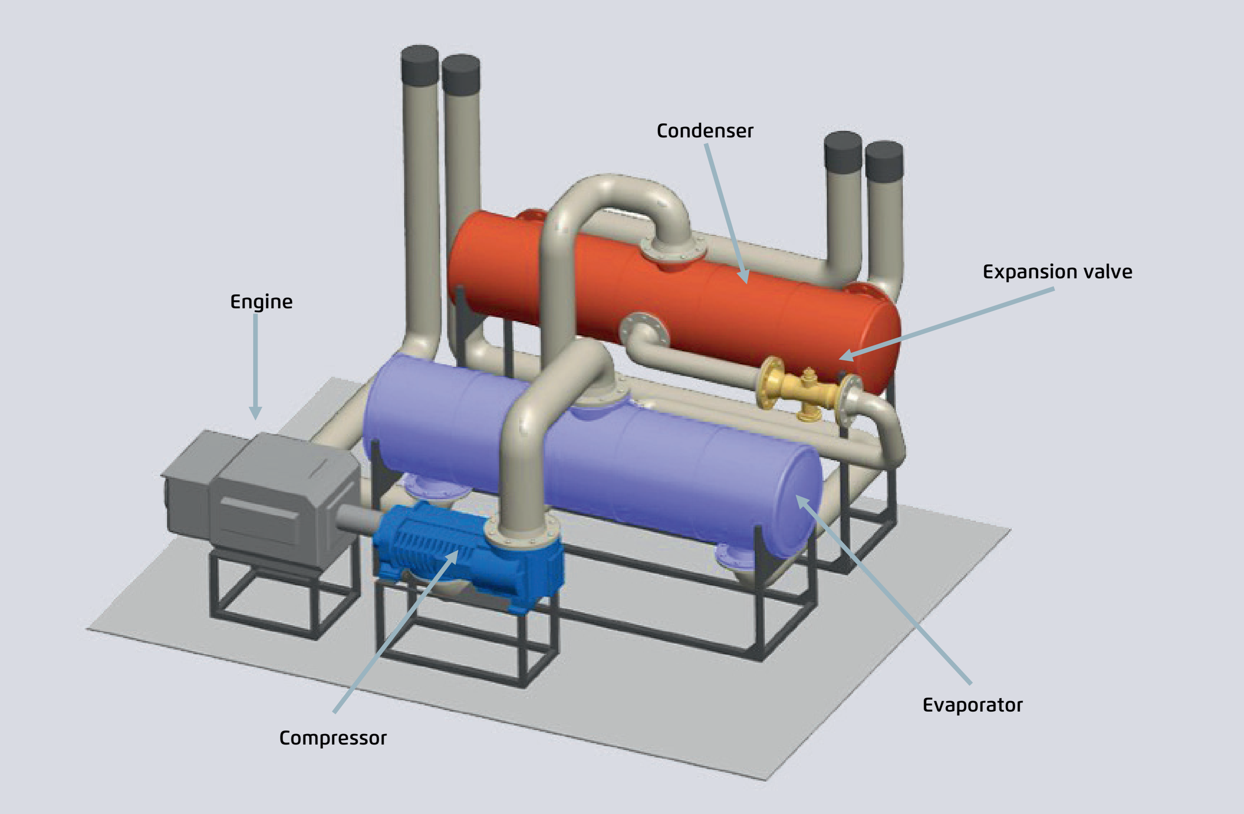
necessary to weigh up the potential benefits against the higher investment requirements. With increasing full load hours, the lower consumption costs can outweigh the higher investment costs, so the impact of a specific configuration on the cost-effectiveness of the overall investment can be determined on the basis of the calculated full load hours.

The selection of the appropriate configuration enables an optimum system design for the specific temperature levels of the heat source and heat sink. A common configuration to increase the efficiency of heat pumps is the use of an internal heat exchanger (IHX) between the condenser outlet and the evaporator outlet. The additional over-heating of the refrigerant before compression enables a reduction of the required compressor capacity and thus an increase in the COP, in addition to avoiding droplet impact in the compressor. A reduction in the pressure ratio to be overcome by the compressor can also be achieved through the integration of an ejector, which combines the high-pressure refrigerant with the flow at the evaporator outlet after it leaves the condenser and thus compresses it to a higher pressure level.

Multi-stage compressors operating at different pressure levels have become established on the market as a means of bridging large temperature lifts. Interstage cooling takes place between the compressor stages.

So-called economisers or flash tanks can also be integrated as an additional means of increasing efficiency. This involves injecting superheated

Schematic representation of a large-scale heat pump | Figure 24



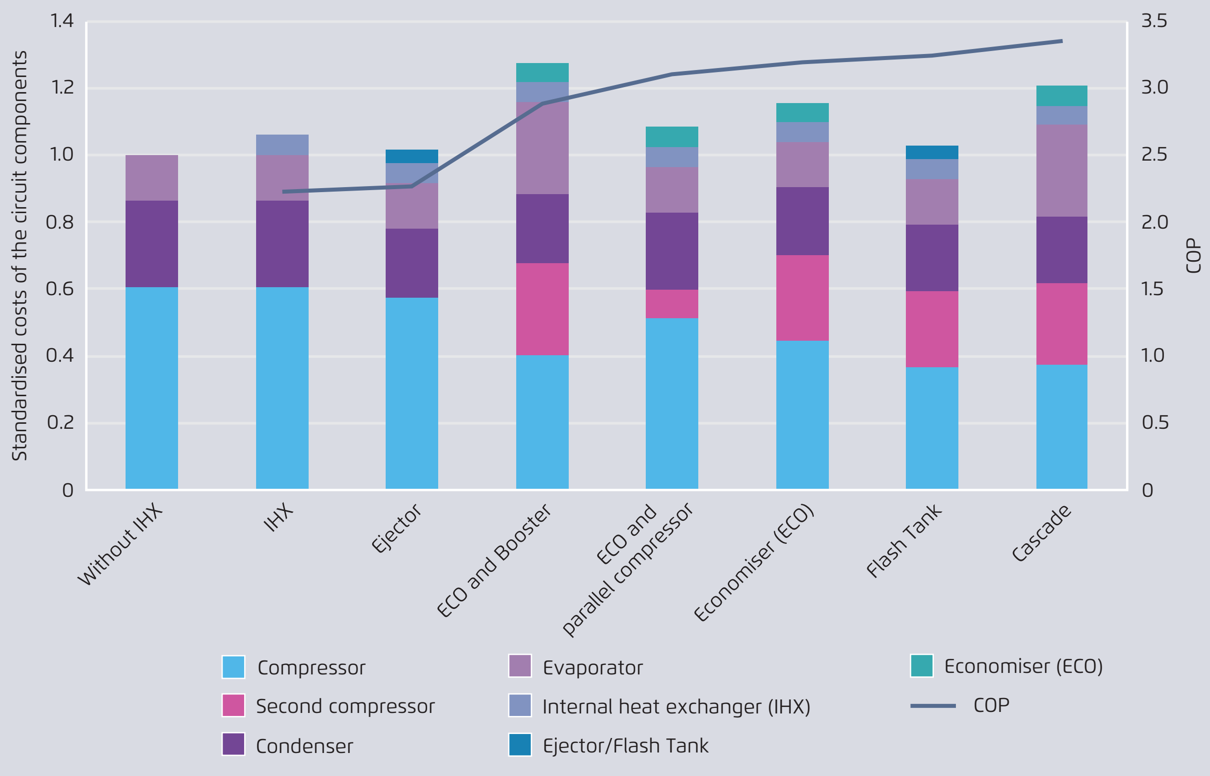
Fraunhofer IEG (2023)

steam (economiser) or saturated steam (flash tank) between two compressor stages or directly into the compressor, which reduces the required pressure ratio and thus the power required to drive the compressors. The economiser can also be connected to another compressor (parallel compressor) or another evaporator (booster).

An additional evaporator enables the use of heat sources with different temperature levels. For high temperature lifts, it is also possible to use two refrigerant circuits with different refrigerants, connected in series. A heat pump cascade of this kind allows the compressors and refrigerants to be optimally configured for the relevant temperature range.

There is a good prospect of further increases in efficiency in the future through waste heat recovery and the integration of expanders. In addition to such already established technologies, there are additional possibilities for further increases in the efficiency of large-scale heat pumps in the future. For example, the waste heat from the electric drive or from the compressor can be used directly through heat recovery. Another possibility for increasing the COP is the integration of an expander. Here, instead of expansion via the expansion valve, mechanical work is recovered for driving the compressor. Transcritical circuits are particularly suitable for implementing this technology, as they enable the refrigerant to be expanded in a single phase.

Illustrative impact of different configurations on the costs of the circuit components and the COP under constant parameters* — Figure 25



Fraunhofer IEG based on Mateu-Royo et al. (2021). * Refrigerant (R245fa), temperature lift (60K) and sink temperature (130 °C) are constant for all configurations.

5.2 The compressor as key component

The design of the individual components of a large-scale heat pump must meet the requirements of the heat source and the heat sink. Since the compressor determines the temperature and performance range as well as the efficiency and is also the most expensive single component of a heat pump, it will be discussed separately here.

Multi-stage reciprocating or piston compressors, single- or twin-shaft high-pressure screw compressors and multi-stage turbo compressors are all established on the market as compressor technologies for large-scale heat pumps (Arpagaus 2020). Scroll compressors are also widely used in heat pump technology, but due to the small volume flows they are usually found in power classes below 500 kW. Due to this technical distinction, the threshold for the definition of a large-scale heat pump was set at 500 kW for this study. Figure 26 compares compressor technologies in terms of their achievable heating outputs and temperature lifts, as well as their suitability for flexible modes of operation. This ranking serves as a guideline and is not to be regarded as applicable to the overall performance of the individual compressor.

In the field of large-scale heat pumps, piston compressors are mainly used for smaller performance classes with correspondingly smaller volume flows, as the highest pressure ratios and thus temperature lifts can be achieved with them due to the positive displacement principle. In addition, this pump design is efficient in the partial-load range. On the other hand, there are high noise emissions and vibrations, which can affect where the heat pump can be used.

Screw compressors are mainly used for higher capacities up to the megawatt range. Due to their excellent cooling capability, the possibility of oil-free operation and of achieving high pressure ratios, screw compressors are also suitable for wide temperature ranges right up to high-temperature applications. In addition, they are regarded as low-maintenance and robust over a long service life with high efficiency over a wide power range.

Turbo compressors have the largest volume flows and thus heating capacities, up to 70 MW (Siemens Energy 2023b). This compressor technology can also be operated oil-free thanks to innovative magnetic bearings. However, it is used less frequently in smaller power classes due to the low incremental pressure rise per stage and the associated high drive energy requirement. In addition, turbo compressors cannot be optimally designed to be controllable over wide performance ranges because they are based on a different physical operating principle from piston and screw compressors. The pressure is not increased by displacement, but by impulse transmission and deceleration.

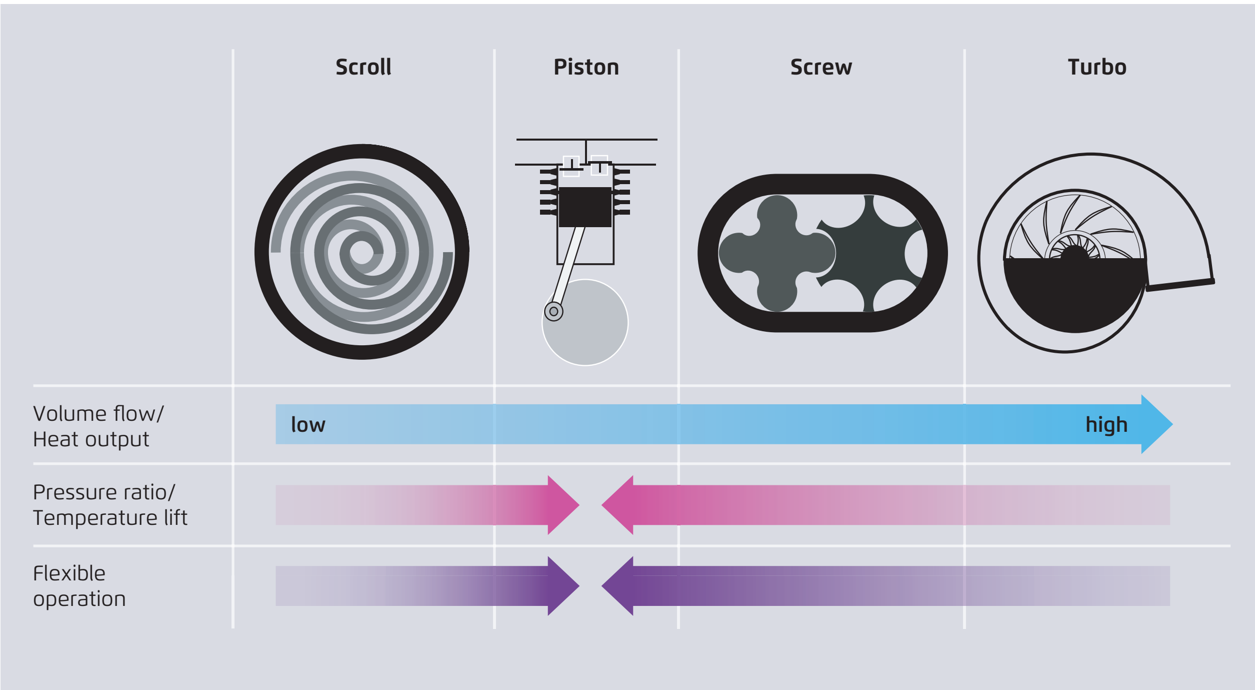
The main need for development in compressor technology is with regard to new refrigerants, more flexible modes of operation and higher sink temperatures. For the compressor as key component of a heat pump, the main areas where development is needed are in adaptation to new refrigerants, more flexible modes of operation and higher sink temperatures. This may mean redesigning and further developing the cooling or lubrication and mechanical components such as bearings and valves, seals and other plastics. To improve heat resistance, for example, oil-free compressors are being tested with a focus on innovative bearings and direct injection of refrigerants. The use of heat-resistant materials and new cooling technologies is also being considered by several manufacturers. As process steam generation by means of open large-scale heat pumps is becoming increasingly important, there is also a need for further development and optimisation of mechanical steam compressors.

As described in Chapter 3.2, the operation of large-scale heat pumps in a way that supports the network requires modes of operation that are flexible and driven either by heat or electricity. This includes, in particular, designs that enable a wide operating range with the most efficient and robust performance possible in the partial load range, as well as rapid load changes and start-up and shutdown processes. For intraday trading and the minute reserve, this means that in future large-scale heat pumps must be able to respond to start-up and shutdown commands at 15 minutes notice at most. Participation in the secondary or primary control reserve market would entail even shorter response times and higher prequalification requirements (50Hertz Transmission GmbH et al. 2022).

The control and regulation systems of large-scale heat pumps must be upgraded so that they can react dynamically to a changing electricity market situation. In large-scale heat pumps, the output is regulated by adjusting the compressor speed with the help of a frequency converter. The compressor is therefore the main determinant of flexibility. Positive displacement machines such as reciprocating piston and screw compressors can be used much more efficiently over a wide operating range than turbo compressors. Turbo compressors, on the other hand, enable significantly higher heating output. Since district heating applications require high output classes with simultaneously lower full load hours from year to year and higher flexibility, a trade-off must be made between the operation of stand-alone large-scale systems and the modular operation of several large-scale heat pumps with optimised output regulation.

Several smaller heat pump units can offer advantages in terms of standardisation of production and planning, in addition to the potential increase in flexibility. However, the modular mode of operation faces higher investment costs compared to a single unit, which is why an upscaling of reciprocating

Heat output, temperature lift and flexibility of large-scale heat pumps depending on different compressor technology types — Figure 26



Fraunhofer IEG (2023)

piston and screw compressors for higher performance classes is being pursued by some manufacturers.

5.3 The importance of environmentally friendly refrigerants

The choice of the correct refrigerant for a heat pump is first of all a technical question. A medium must be found with thermodynamic properties that promise optimum efficiency for the source and sink temperature determined by the application and for the selected circuit configuration. For certain temperature ranges, various refrigerants can be considered.

In heat pumps with flow temperatures up to 80 °C, the refrigerants R410a and R134a are widely used today. Ammonia (R717), a natural refrigerant, has a similar application range with sink temperatures up to 110 °C. For flow temperatures up to 80 °C, propane (R290) is also an alternative refrigerant.

Heat pumps with carbon dioxide (R744) as refrigerant are operated at temperatures of 80 °C to 120 °C on the sink side and below 30 °C on the source side (Arpagaus 2019). A very efficient mode of operation for CO_2 heat pumps is achieved with large differences between the flow and return temperatures. In this case, the heat transmission is achieved by gas cooling with decreasing temperature of the refrigerant instead of isothermal condensation.

For high-temperature applications above 120 °C, hydrocarbons such as iso-butane (R600a), butane (R600) or pentane (R601) are also suitable. Many manufacturers of large-scale heat pumps also use synthetic hydrofluoroolefin (HFO) refrigerants for the high-temperature range. For the temperature range above 120 °C, options include the HFO refrigerants R1336mzz(Z), R1233zd(E) and R1234ze(Z).

The use of water (R718) can be advantageous for very high flow temperatures of 200 °C and beyond for the provision of industrial process heat or process steam.

Refrigerants for heat pumps can be either natural or synthetic. These differ mainly in terms of their environmental friendliness. The influence of the refrigerant on the efficiency of a heat pump circuit is illustrated in Figure 27.

Although synthetic refrigerants are still widely used today, they and their degradation products have a global warming potential and will therefore be almost universally banned in the future. Until the 1990s, chlorofluorocarbons (CFCs) were the main refrigerants used, but they damage the ozone layer of the atmosphere either directly or indirectly through their degradation products. In Germany, an ozone depletion potential (ODP) of zero has been mandatory since 1995, and most ozone-depleting refrigerants have therefore been replaced by hydrofluorocarbons (HFCs). However, these replacements still have a notable global warming potential, as shown in Table 2.

The global warming potential (GWP) measures the relative contribution of a greenhouse gas to global warming compared to the same mass of CO_2. The GWP of refrigerants has been regulated by the European F-Gas Regulation since 2015. Currently, a gradual reduction of HFC refrigerants to 21 percent is planned by 2030, which is why it can be assumed that refrigerants with a high global warming potential will be replaced over time. Another requirement for refrigerants is that their residence time in the environment should be as short as possible. This applies not only to the refrigerant itself, but also to its degradation products.

The degradation products of some HFOs include per- and polyfluorinated alkyl substances (PFAS), often referred to as "forever chemicals", which can accumulate in the environment and in humans – another reason for their ban. PFAS, which are used in many everyday products primarily for their grease-, dirt- and water-repellent properties, Coefficients of performance (COPs) for different refrigerants in a single-stage circuit* Figure 27

Fraunhofer IEG based on Mateu-Royo et al. (2021). * Temperature lift (60 K), sink temperature (130 °C) and circuit configuration constant for all refrigerants

are suspected of causing cancer, among other things. For this reason, in February 2023 the European Chemicals Agency ECHA presented a proposal from five EU states to ban all compounds of this substance class within the next twelve years (ECHA 2023). A decision to impose this ban under the REACH Regulation is expected in 2025. The exclusion of refrigerants via the PFAS regulations could lead to them being banned even faster than under the F-Gases Regulation. Such a ban does not stand in the way of the technical implementation of heat pump technology, but it impacts on some investment decisions already made by manufacturers and might thus influence the speed of the market ramp-up.

The risks arising from the flammability and toxicity of some natural refrigerants are manageable. Some natural refrigerants, unlike synthetic refrigerants, have the disadvantage of being flammable or toxic. Flammability mainly applies to the homologous series of hydrocarbons, and toxicity to ammonia. The natural refrigerants CO_2 and water are unproblematic in both respects. The risks from flammability and toxicity can be controlled by technical safety features. The safe handling of much larger quantities of these agents in industrial plants is standard technical practice.

For subcritical use, the evaporating temperature and the critical temperature of a refrigerant specify the lower and upper temperature limits. The mechanical load on the high-pressure components can be reduced by a low critical pressure. Higher operating pressures, however, conversely lead to higher volumetric refrigeration capacities and thus lower installation space requirements. This is especially true for CO_2 as a refrigerant. In addition, the refrigerant must be tailored to the materials and oils used in the circuit, especially with regard to material deposits, embrittlement and the associated changes in the long-term properties of the materials used. The volumetric heat capacity dictates the dimensions of a heat pump. There are additional requirements for the refrigerant in terms of the required pressure ratio, cost-effectiveness and availability on the market. The choice of refrigerant is ultimately a compromise between all of the above aspects (Arpagaus 2019). Table 2 shows the properties discussed above for selected refrigerants. The table is divided into overall type of refrigerant and then subdivided into individual refrigerants.

Following the F-Gas regulation and the debate on PFAS, the use of natural refrigerants is becoming the focus of further research and development in relation to heat pumps using a cold steam process. This includes both the testing of new refrigerants and the redesign and optimisation of the circuits as well as of key components such as compressors and heat exchangers. In addition to achieving higher efficiencies and temperatures as well as more flexible modes of operation, the aim is to ensure the safe and ecological operation of large-scale heat pumps. In addition to the very promising potential of the use of water, the transcritical use of hydrocarbon refrigerants such as iso-butane, butane or pentane offers the possibility of achieving sink temperatures above 200 °C (Pachai A. C. et al. 2021).

Environmental properties of selected refrigerants of different categories with regard to climate impact, toxicity and flammability — Table 2

Category	Refrigerant	GWP	Toxic	Flammable
HFCs	R245fa	858	Yes	No
	R134a	1 300	No	No
	R410a	2 088	No	No
HFO	R1234ze (Z)	< 1	No	Yes
	R1233zd (E)	1	No	No
	R1336mzz (Z)	2	No	No
Natural	R717 (Ammonia)	0	Yes	Yes
	R718 (Water)	0.2	No	No
	R744 (CO_2)	1	No	No
	R290 (Propane)	3	No	Yes
	R600 (Butane)	4	No	Yes
	R601 (Pentane)	5	Yes	Yes
	R600a (Isobutane)	3	No	Yes

Fraunhofer IEG based on Arpagaus (2019)

6 The market for large-scale heat pumps: products, manufacturers, industrial policy

6.1 The market for large-scale heat pumps: products and manufacturers

Although the market for large-scale heat pumps, unlike that for smaller units, is still at an early stage of maturity, a large number of different technological options are already available on the market. A market analysis identified 36 manufacturers of commercially available large-scale heat pumps for heating capacities above 0.5 MW. In addition, there are other manufacturers who as plant engineers are developing individualised concepts for large-scale heat pumps. Besides established manufacturers, there are also large companies from the fields of air conditioning and refrigeration technology, or from process technology or power plant technology, as well as a number of start-ups in the heat pump market.

Currently, most large-scale heat pumps up to a heating capacity of 1 MW are offered as part of a standardised product range. As described in Chapter 2.4, at least a quarter to a third of all large-scale heat pump projects in Germany will be below this heating capacity. Above 10 MW, on the other hand, highly customised individual systems predominate. The greatest potential for further standardisation therefore lies in the output range in between.

Figure 28 shows an overview of the maximum flow temperatures and heating capacities and of the compressor technologies used in mechanically driven large-scale heat pumps with a Technology Readiness Level (TRL) of 9. A detailed list of these large-scale heat pumps is provided in the appendices (see A.3, Figure 42). The spectrum of large-scale heat pumps covers a heating capacity range of up to 70 MW, although significantly higher heating capacities can be achieved through modular parallel operation.

For large heating capacities above 10 MW, turbo compressors are predominantly used. The highest temperature differences, on the other hand, are achieved with piston compressors. Up to flow temperatures of 120 °C and heating capacities of 10 MW, products with piston compressors or screw and turbo compressors are used to cover a wide range of applications. Scroll compressors, on the other hand, are only used in smaller output and heating classes. Temperatures above 200 °C are currently mainly achieved by open heat pump processes with so-called mechanical vapour compression (MVR) for supplying process steam (see A.3, Table 8).

Large-scale heat pumps are already available on the market today in the temperature range required for district heating. For flow temperatures below 120 °C, the market already offers a wide range of large-scale heat pumps, with 66 different products available. Since 90 percent of district heating networks are currently operated with flow temperatures below 110 °C (see Figure 2), the technology for this sector is thus largely established. At higher temperatures, however, the range of large-scale heat pumps is much smaller. Above 140 °C, the market is not yet fully covered and is in part limited to prototypes. There is therefore a need for further innovation in heat pump technologies in terms of increasing the sink temperature and the temperature lift, especially for tapping into the industrial sector. Products for this temperature range are therefore being developed not only by established manufacturers of large-scale heat pumps, but also by newly established companies and existing companies now entering the market for large-scale heat pumps.

Maximum flow temperatures and heating capacities of available large-scale heat pumps — Figure 28

Fraunhofer IEG (2023) based on Figures 42 in Annex A.3

The IEA HPT Annex 58 (see A.3, Figure 43) provides an overview of technologies already available on the market (TRL = 9) and of high-temperature heat pumps under development or close to market maturity (TRL < 9) (IEA 2023b). For higher temperatures, either existing technologies are adapted and modified or new technologies are developed. The TRL of large-scale heat pumps decreases with larger temperature lifts. At the same time, this is also the area where performance has improved the most due to the research carried out in recent years. This is mainly due to further technical improvements in optimised components such as the compressor or the heat exchangers, to innovative circuit interconnections and to adjustments to the regulation system and mode of operation. Figure 29 shows the achievable COP for different large-scale heat pumps depending on the temperature lift required.

Digression: overview of other heat pump technologies

In addition to closed-loop compression heat pumps, other heat pump technologies which are suitable for particular applications have become established on the market. There are also promising new technologies that have already reached market maturity or are being tested in research projects. Here, the focus is especially on increasing the sink temperature and the temperature lift as well as on more flexible modes of operation based on natural refrigerants. An overview of other market-ready and novel heat pump technologies can be found in Appendix A.3 (see Table 8).

COP and temperature lift for large-scale heat pumps currently available on the market with different source and sink temperatures

Figure 29

Fraunhofer IEG (2023) based on Figures 42 and 43 in Annex A.3

6.2 The manufacturer's perspective: greater planning certainty as a prerequisite for larger production volumes and shorter delivery times

The manufacturers of large heat pump units are key to the successful roll-out of this technology in Germany. Many of them are active throughout the European market or worldwide and therefore already have a relatively broad market-ready product range for various applications in their portfolio (see Chapter 6.1).

In the course of this study, Fraunhofer IEG was in direct contact with many of these companies on specific questions related to the development potential of the technology (e.g. achievable temperatures, COPs and flexibility) and on their plans regarding the establishment of further production capacity. In addition, a workshop on the challenges and opportunities of the roll-out of large-scale heat pumps in Germany was held in February 2023 together with 21 representatives from 15 manufacturers. The insights gained from this have been incorporated into this study (predominantly in Chapter 5) and are summarised below.

If indications of sustained high demand become more robust and investment conditions more stable, manufacturers are ready to double their production capacity within a few years. The manufacturers are convinced that the path to a climate-neutral energy system in Germany involves the rapid introduction of large-scale heat pumps into the growing district heating networks.

At present, however, the manufacturers of large-scale heat pumps do not yet see the kind of increase in demand that is assumed in the T45 scenarios, for example (see Chapter 3.1). Nevertheless, they perceive from the increase in enquiries and feasibility studies that interest in large-scale heat pumps is steadily growing on the part of equipment buyers and operators from the district heating and industrial sectors.

At the same time, however, they believe that large-scale heat pumps are still in competition with gas-based heating systems – not only for customers, but also for those manufacturers who simultaneously offer alternative heat supply technologies, such as those based on the combustion of fossil gas or green hydrogen. In this internal competition between manufacturers for limited human and financial resources, due in part to unclear political signals, it is therefore primarily current (confirmed) demand that determines investments in production capacity.

Most manufacturers are therefore somewhat reluctant to build up production capacity until the interest in large-scale heat pumps is reflected in their order books. If demand increases significantly, all manufacturers are confident that they would be able to double their production capacity within just a few years. If these new factories are built in Germany, this will also have advantages in terms of sectoral industrial policy, as it will secure future-proof industrial jobs, valuable know-how and system-relevant value creation networks.

Opportunities for innovation and the need for action from the manufacturers' perspective

Optimisation of capital expenditure: lower prices through economies of scale in production, more standardised product components for more application areas, and higher performance classes. Further standardisation of products and components is possible, and in principle it is in the interest of manufacturers. However, many manufacturers are still frequently confronted with requests for customised designs. Below 1 MW, most heat pumps are already highly standardised products. Above 10 MW, heat pumps become highly customised products, frequently supplied through large EPC (Engineering, Procurement and

Construction) contracts. Most heat pumps for district heating systems are expected to be in the 1 MW to 10 MW power range. For the ramp-up in this market segment, the main missing factors are the wider availability of standardised equipment and a sufficiently proactive field of engineering service providers to support customers in the procurement process.

Larger units enable a significant reduction in overall costs in relation to the installed capacity. For example, for a manufacturer's product portfolio, the costs per installed MW of heat output above 10 MW are only about half as high as for the 2-5 MW class.

The ratio between electricity and gas prices is crucial for optimising operating costs. Achieving higher COPs and developing more flexible installations for future use in district heating are possible. Based on their experience in other European markets, many manufacturers are also convinced that sales of their products in Germany will only accelerate when all market players have sufficient planning certainty. This includes confidence that fossil gas and electricity prices, taking into account carbon pricing and other levies, surcharges, taxes and subsidies, will develop in such a way that the operation of large-scale heat pumps will be economically more attractive in the future than the operation of gas-based alternatives.

Up to now, manufacturers have developed and designed their large-scale heat pumps primarily for long operating cycles each year, as this is predominantly how they are used, especially by industrial customers. In such projects, economic viability in terms of investment costs and operating hours depends primarily on the operating costs – i.e. the COP and the electricity supply costs. The level of site-specific capital expenditure (CAPEX) has therefore often played a subordinate role up to now. The prospect of shorter annual operating hours in district heating is now increasing the pressure on manufacturers to focus more on the potential for reducing the acquisition costs for large-scale heat pumps.

The same applies to the increasing requirements for flexible and system-supporting operation of large-scale heat pumps. Some manufacturers therefore believe that it is possible to optimise the design and operating performance of their large-scale heat pumps in such a way that the COP in flexible operation could be improved by 10 to 20 percent.

The F-Gas and REACH Regulations have an impact on the availability of synthetic refrigerants and on the investment plans of large-scale heat pump manufacturers. Manufacturers are aware that the flammability and toxicity of refrigerants are important issues for many of their customers.

However, the general trend towards natural refrigerants is recognised by virtually all manufacturers of large-scale heat pumps. Nevertheless, the current discussions at EU level about the legal permissibility of certain refrigerants are leading to increased planning uncertainty for manufacturers, both in terms of the prospects for their existing production lines and of ongoing development activities and planned investment decisions (see Chapter 5.3). From the manufacturers' point of view, grandfathering of existing production capacities and plants already in operation as well as recycling programmes could provide a remedy here.

Remedying the shortage of skilled workers is necessary both for building up production capacity and for planning and executing large-scale heat pump projects. Manufacturers of large-scale heat pumps, as in many other fields, are confronted with the shortage of skilled workers – both in their own companies and among their customers.

To support a rapid and large increase in production capacity, some manufacturers can envisage a transfer of technology and personnel from the production of conventional gas boilers and CHP plants as well as from other sectors, such as the production of combustion engines for the automotive industry, due to similar system components and processes.

At the same time, however, the manufacturers doubt whether the municipal utilities, district heating suppliers, project developers and construction companies, which are also all affected by the shortage of skilled workers, would be able to keep up with this pace in the short term. At present, they say, manufacturers are being asked by their customers to provide planning services themselves, even though this is not part of the core business of most manufacturers. Joint action by policymakers, chambers of commerce, trade unions and companies to strengthen education and training as well as the retraining of skilled workers is therefore important for the market for large-scale heat pumps.

Clear investment signals, better communication and an industry-wide dialogue at federal level are urgently needed to accelerate the roll-out of large-scale heat pumps. International manufacturers especially are not always familiar with the German incentive and support programmes. In addition to better communication about the investment conditions in Germany, many manufacturers would also like to see clearer positive investment signals and more planning certainty from political decision-makers.

To accelerate the energy transition, several (small-scale) heat pump summits and sector dialogues on renewable energy and electricity grids already took place in 2022. According to its workshop report of 9 March 2023, the BMWK is now planning to hold a so-called district heating summit in the summer of 2023, in which new specifications for the operation of district heating systems are to be discussed with key stakeholders (BMWK 2023). "Key stakeholders" are, in particular, the manufacturers of large-scale heat pumps, district heating suppliers, municipalities, licensing authorities and chambers of commerce. This summit offers an opportunity to establish dialogue between the key players and to ensure more planning security on both the manufacturing and demand sides.

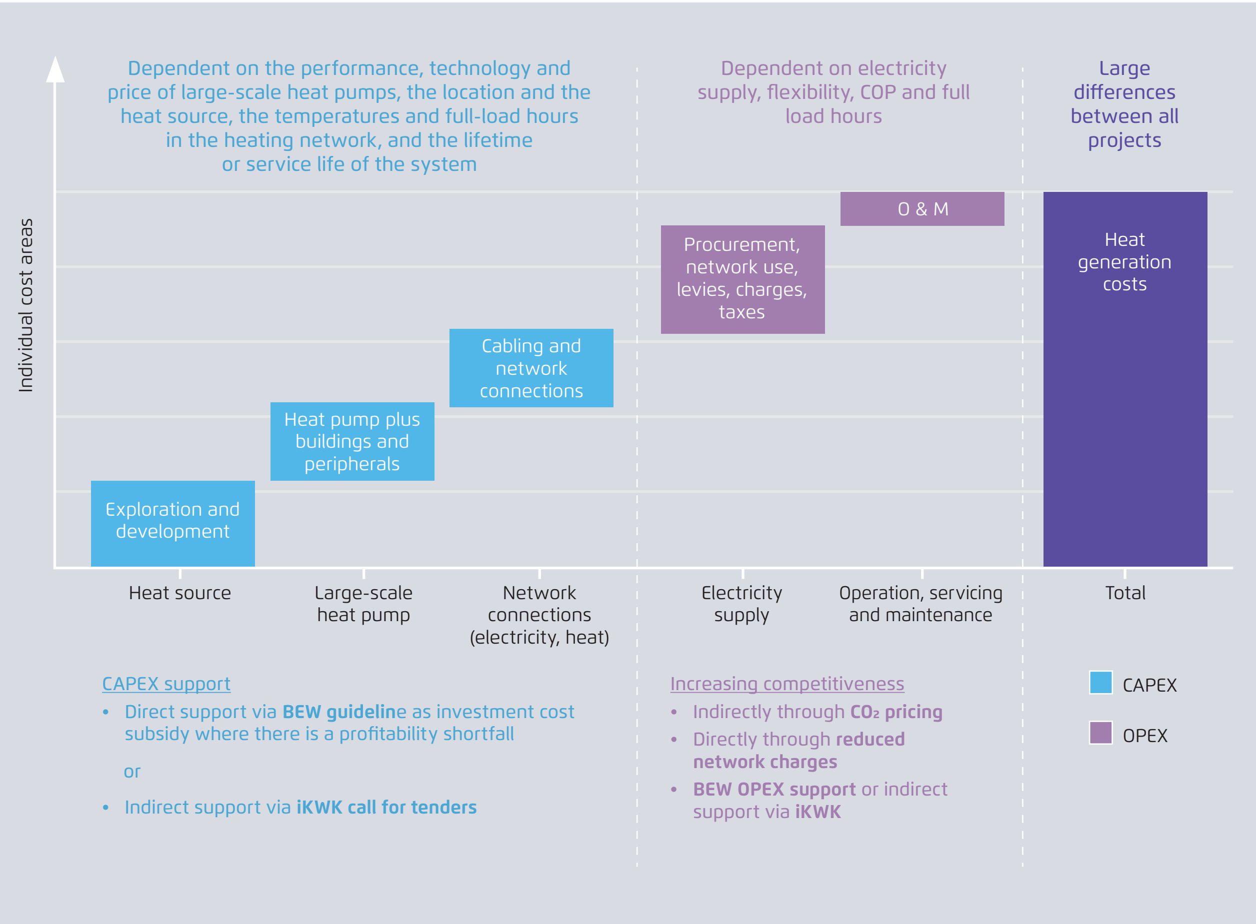
7 Regulatory and economic framework, incentive systems and financial support possibilities in Germany

7.1 Factors affecting the profitability and competitiveness of large-scale heat pump projects

The investment incentives for large-scale heat pumps and their profitability depend on many factors. With regard to the various cost elements of a large-scale heat pump project, the following factors are particularly influential (see Figure 30):

→ CAPEX depends on:
- Nature, source temperature, location and access requirements of the heat source

Economic factors affecting large-scale heat pump projects — Figure 30



Fraunhofer IEG (2023)

- Performance, technology and price, and location of the large-scale heat pump (including land, building, peripherals, planning and construction)
- Temperature level and full load hours of the heat sink
- Costs of network connection to electricity and district heating systems
- Lifetime/service life of the large-scale heat pump system

→ OPEX depends on:
- Efficiency or COP and full load hours of the large-scale heat pump
- Load profile of the plant (system-supporting operation during periods of low electricity prices)
- Electricity procurement strategy, for example drawing electricity from the grid and procuring it on the wholesale market, long-term green power purchase agreement (PPA) or in-house electricity supply
- Network use charges and other charges, levies and taxes incurred

As shown in Figure 30, a number of measures have recently been implemented in Germany to improve the profitability of large-scale heat pumps. These measures were and are primarily aimed at reducing operating expenses – indirectly through the introduction of carbon pricing on fossil fuels in sectors not covered by the emissions trading scheme, and directly through the elimination of the EEG levy and the exemption from the CHP and offshore grid levies.

However, investment and operating cost support is still necessary to enable a profitable operation of large-scale heat pumps in Germany under the current framework conditions and to stimulate investment in the decarbonisation of district heating systems. This is discussed in the explanatory memorandum accompanying the European Commission's approval of the BEW Guideline with respect to the law on state aid (EC 2022) and in Billerbeck et al. (2023). The financial support is intended to help reduce competitive disadvantages compared to fossil gas and to keep the price of district heating at a level that is acceptable to heating customers. Further increases in carbon prices or reductions in heating prices on the consumer side can help to reduce the profitability shortfall and thus the need for subsidies.

The following are the main support instruments currently available to help close the remaining profitability shortfall and avoid excessively high district heating prices:[11]

→ Investment and operating cost subsidies via BEW (see Chapter 7.3)
→ Participation in a call for tenders under the 'innovative CHP' programme (innovative Kraft-Wärme-Kopplung, iKWK), or award of a bonus for innovative renewable heat under the CHP Act (Kraft-Wärme-Kopplung Gesetz, KWKG) (see Chapter 7.4)

With the revision of the Buildings Energy Act (GEG), new district heating systems are to be required to use at least 65 percent renewable energy and waste heat. According to the draft bill published in April 2023, this is to apply to projects starting construction on or after 1 April 2024. For existing district heating systems and network extensions, a transformation plan is to be drawn up by 31 December 2026 that demonstrates how the system will be switched to at least 50 percent renewable energy and waste heat by 2030 and be completely decarbonised by 31 December 2044.[12]

11 In addition, there are other subsidy programmes at federal and state level that also support large-scale heat pumps. However, these are of no or only minor importance for the district heating sector and the nationwide roll-out of large-scale heat pumps and are therefore not considered further in this study.

12 § 71b GEG draft, see: Draft Federal Government Bill. Draft bill to amend the Buildings Energy Act, to amend the Heating Costs Ordinance and to amend the Sweeping and Inspection Ordinance, accessed at: https://www.bmwsb.bund.de/SharedDocs/gesetzgebungsverfahren/

This further restricts the scope for fossil-based heat supply options, increases planning certainty for carbon-free alternatives and thus further improves the competitive situation for large-scale heat pumps.

The cost-effectiveness of industrial heat pumps differs from that of large-scale heat pumps used in district heating systems due to several factors. The most significant are the higher sink temperatures and the significantly higher utilisation rates, with an average of 6 000 full load hours. The economic viability of industrial heat pumps was examined in the study "Power-2-Heat: Gas savings and emissions reduction in industry" by Agora Industry and FutureCamp (Agora Industry and FutureCamp 2022). Beyond the support options for industry presented here, there are various others, in particular the Federal Support for Energy and Resource Efficiency in Industry (Bundesförderung für Energie- und Ressourceneffizienz in der Wirtschaft, EEW).

Competitiveness of large-scale heat pumps compared to other heat supply options

The economic viability and public acceptance of a large-scale heat pump project depends not only on the heat production costs of alternative technologies for carbon-free or climate-neutral heat production, but also on the current (district) heat supply prices, which include the network costs in addition to the generation costs.

Since the focus of this study is on the transformation of district heating generation by means of large-scale heat pumps, the network costs included in the district heating prices are not considered here. Likewise, the heat production costs of other technologies (such as fossil gas, solar thermal, biomass or green hydrogen) for centralised or decentralised heat supply are not examined in this study or compared with those of large-scale heat pumps. Numerous academic and private-sector studies are already available on this subject, for example: Billerbeck et al. (2023); UBA (2023a); Gerhardt et al. (2021); Agora Industry and FutureCamp (2022). The main findings of these studies can be summarised as follows:

- → The location factors and network parameters in the (district) heating sector are so diverse that there is no single optimal solution for all cases.
- → Due to the limited attention paid to this technology in the past, its higher technical complexity, its lower degree of standardisation and the as yet very low production quantities, large-scale heat pumps have noticeably higher investment costs than conventional heat generation technologies based on fossil gas.
- → There is still no level playing field in Germany between green electricity-based climate-neutral heat generation and fossil gas-based CO_2-emitting heat supply. The higher the carbon price and the lower the ratio of the retail price of electricity to gas, the more competitive large-scale heat pumps are.
- → As long as there is no level playing field or other incentives for the climate-neutral transformation of district heating networks, it will remain necessary for the resulting profitability shortfall for large-scale heat pump projects to be closed by means of subsidies. The profitability shortfall is in turn dependent on the level of a socially acceptable district heating price and the costs of alternative heat supply in the heat supply area in question.
- → A rising carbon price will cause the heating cost benchmark, which is currently still largely based on fossil gas, to rise from year to year. This development alone should lead to a gradual narrowing of the profitability shortfall for large-scale heat pumps, and thus also to a reduction in the need for subsidies.

This study builds on this knowledge and therefore concentrates in the following on the analysis of the heat production costs of a number of case studies of large-scale heat pump projects. The purpose of this

Webs/BMWSB/DE/Downloads/kabinettsfassung/geg-20230419.pdf;jsessionid=E3E7FA71D3250342C67F-80F2A57E2AFF.1_cid364?__blob=publicationFile&v=1.

approach is to enable an assessment and comparison of the different heat sources, design variants, cost assumptions and value drivers. This should give potential investors, plant operators and policymakers in the energy field more guidance for their project assessment and decision-making.

7.2 Heat generation costs of large-scale heat pump projects for different heat sources without subsidies

The dimensions and the field of application lead to project-specific investment costs. The capital expenditure for a large-scale heat pump project consists of the costs for the large-scale heat pump, the exploitation and connection of the heat source, the construction work, and the utilities connection, which includes the electrical connection as well as the measurement and regulating technology. The many different selection and configuration options for the heat pump technology are also reflected in the amount and breakdown of the investment costs – and consequently also of the operating costs.

The heat source and the local site conditions have the greatest influence on the unit investment costs of a large-scale heat pump project. Furthermore, the capacity of the large-scale heat pumps is important. This in turn results in specific cost-relevant requirements for the selection and design of critical components such as compressors and heat exchangers as well as the individual configurations.

In addition, the costs for planning and for the heat storage must be taken into account. For the heat storage capacity that is required for system-supporting operation, an identical investment cost is assumed for all heat sources. The cost calculation is based on the demand for the heat storage capacity in the T45-Electricity scenario for the year 2030 (at 3 500 full load hours per year) and the investment cost data in Grosse et al. (2017).

Due to the small number of large-scale heat pump projects completed in Germany to date and the limited information available on the investment costs of these projects, the following cost data should be understood as indicative. The market for large-scale heat pumps in Germany is still too immature and too small to enable greater cost transparency and more concrete cost information.

Figure 31 shows the spectrum of unit investment costs relative to the heating capacity for the different heat sources based on price levels in 2022. To show the influence of the plant capacity on the level of costs, the figure includes data for large-scale heat pumps with a thermal capacity of 1 MW (= future mass market) as well as for plants with a thermal capacity of 10 MW.

In addition to illustrating the unit cost advantages of heat pumps with larger capacities, the diagram also shows that geothermal energy (deep, medium-deep and near-surface) has the highest unit investment costs of 2 200 to 3 600 euros per kW. In comparison, the unit investment costs for the use of thermal heat from water bodies (with the focus on river and lake water), wastewater, waste heat and ambient air are significantly lower at 700 to 1 600 euros per kW due to the lower costs involved in tapping the heat sources.

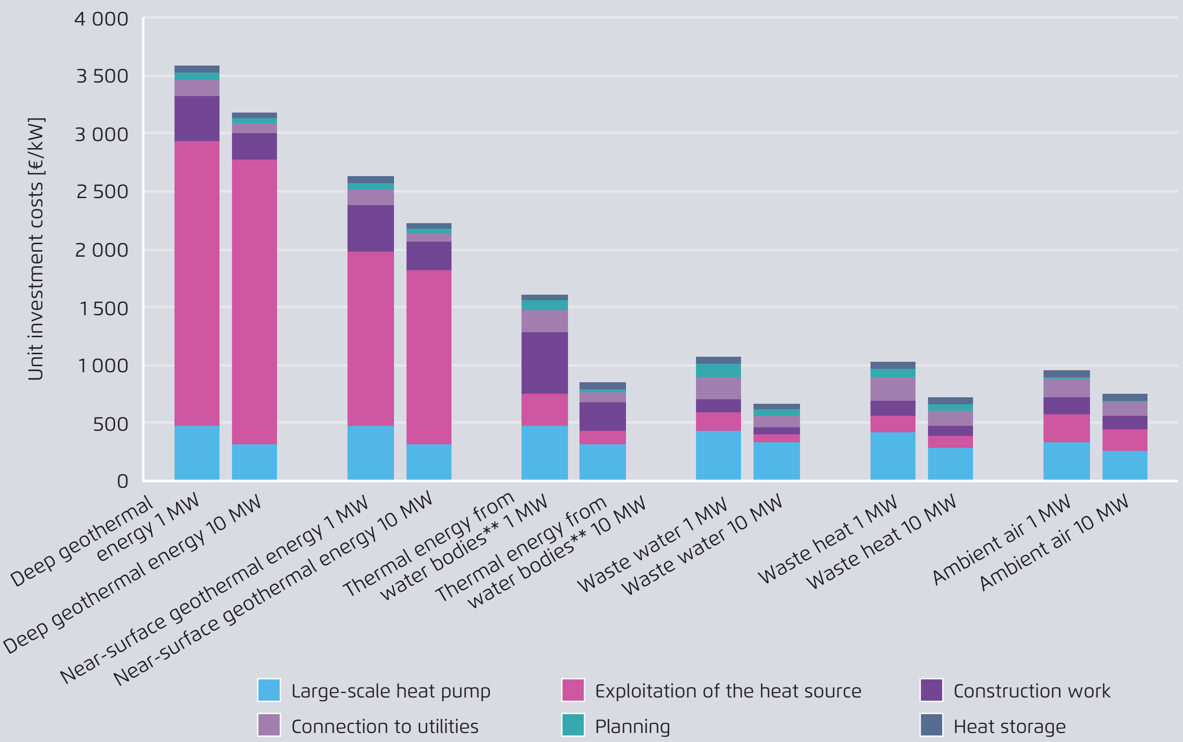
The work and costs involved in the exploitation of and connection to heat sources vary widely. For deep and near-surface geothermal energy, for example, the costs for tapping the heat source amount to about 1 500 to 2 450 euros per kW, which accounts for about 60 to 80 percent of the total investment costs. The unit costs for tapping heat sources are based on an assumed COP of 5.4 for deep geothermal energy and 2.0 for near-surface geothermal energy, as well as average drilling costs of 3 000 euros per kW (for ambient heat, without the drive power for the heat pump). At sites with favourable geological conditions and a low exploration risk, the costs for drilling can be significantly lower, at around 1 800 to 2 200 euros per kW (Bracke et al. 2022).

However, the disadvantage of the high initial investment in geothermal energy is compensated for by the very long service life of the boreholes, which exceeds that of large heat pump units or of other heat sources many times over.

For the other heat sources, too, the exploitation costs for the heat source can vary widely from project to project. For example, the distance of the heat source from the location of the heat pump plays a role. In addition, the heat source may already be tapped, for example in the case of a river water heat pump at a power plant site. The costs for the construction work also depend on the particular local conditions, with construction costs tending to be higher for thermal energy from water bodies and geothermal energy.

The compressor is the most expensive component of a large-scale heat pump. The investment costs decrease with increasing thermal capacity. The cost breakdown of the compression heat pump unit also depends on the configuration of the heat pump, with the compressor as the core component being by far the most expensive. The evaporator and the condenser also both account for a large proportion of the

Impact of the heat source and the other system components on the investment costs of large-scale heat pump projects* Figure 31



Fraunhofer IEG based on Pieper et al. (2018), Grosse et al. (2017) and on authors' data collection. * The analysis of investment costs is based on a limited number of projects. This is due firstly to the comparatively small number of large-scale heat pump projects completed to date and secondly to the limited information available on the investment costs of these projects. ** The proportion shown for the tapping of the heat source from water bodies is to be regarded as low, as it is based on a single project in which the heat source had already been partially tapped.

costs. The costs for components such as internal heat exchangers, pipework and measurement and sensor technology vary depending on the circuit configuration. In total, this results in investment costs for a large-scale heat pump unit of between 250 and 330 euros per kW for a thermal capacity of about 10 MW and between 320 and 500 euros per kW for 1 MW (see Figure 31). The list prices of several manufacturers obtained by Fraunhofer IEG also show decreasing investment costs with increasing thermal capacity. On average, the unit investment costs for a large-scale heat pump of 10 MW decrease by about one third compared to those for a single unit of 1 MW.

For large-scale heat pumps in very high temperature classes, higher unit investment costs can generally be assumed. This is mainly due to the higher technical requirements for core components and to the additional components required, as well as to the more complex and less tried-and-tested technical systems.

In the medium term, a cost reduction can be expected as a result of growing market maturity and increasing demand. This can be assumed in particular for standardised system designs and therefore for large-scale heat pumps of smaller capacity ranges. Grosse et al. (2017) assume a decrease in total unit costs of about 18 percent by 2050 compared to 2020.

Full load hours and electricity supply costs have a significant impact on the cost-effectiveness of using the heat source. The system-supporting operation of large-scale heat pumps in the future energy system will lead to a lower number of full load hours than when integrating today's systems into existing heat generation portfolios and networks. The more flexible the operation is to be, the greater the required heat storage capacity to be kept available and the associated additional investment requirements for the overall system. With a very high number of full load hours, no heat storage is required. At the same time, a change in the operating mode and in the number of full load hours also has an impact on the achievable electricity purchase costs and the network use charges. While the achievable electricity prices fall significantly with a decreasing number of full load hours, the existing system of network charges makes network use more expensive (see Table 3).

The influence this has on the heat generation costs of a large-scale heat pump for each of the different heat sources is examined below by means of a sensitivity analysis for the year 2030.

In accordance with the guideline document VDI 2067, the capital-related costs (investment), the operation-related costs (operation, maintenance and repair) and the consumption-related costs (electricity supply costs) are all taken into account in the determination of annual heat generation costs. The cost structure varies depending on both the heat source and the full load hours. In Appendix A.4, Figure 44, the costs calculated in the different sensitivity analyses for the different heat sources are compared.

The possible use of subsidies for capital costs and/or operating costs is not considered in this sensitivity analysis. This means that all results show the heat generation costs that would arise without the relevant subsidy for the year 2030 under the given assumptions.

The assumptions made in determining the heat generation costs can be found in Table 3. The COPs (see legend for Figure 32) of the heat sources considered are derived on the basis of Figure 22 from averaged assumptions for the sink temperature (100 °C), the relevant source temperatures and the efficiency rating of the large-scale heat pump (50 percent). A version of this sensitivity analysis for a sink temperature of 80 °C is also included in the appendices (see Appendix A.4, Figure 45).

In addition, the influence of different heating capacities and the associated different unit investment costs (see Figure 31) on the heat generation costs of large-scale heat pumps is investigated. For this purpose, large-scale heat pump systems with 1 MW and with 10 MW heating capacity are considered. Variations in electricity purchase costs are also shown for different full load hours to enable an assessment of the competitiveness of current operating modes (3 500 h per year) and of future network-supporting operating modes (1 500 h per year).

Figure 32 shows the results of the sensitivity analysis in the form of the trajectories of the annual unit heat production costs for different heat sources with varying full load hours and electricity supply costs for the year 2030.

The lower investment costs for systems with greater heating capacity have a noticeable effect on the heat generation costs. This is especially true when the system is operated with low full load hours.

Furthermore, the heat generation costs clearly increase with decreasing full load hours, especially for heat sources with high CAPEX levels. It follows that low investment costs play a decisive role with low full load hours, whereas lower operating costs due to high COPs with short operating times are less significant.

Assumptions underlying the sensitivity analysis of the heat generation costs of 1 MW versus 10 MW large-scale heat pumps — Table 3

Heating capacity	Unit	1 MW			10 MW		
Full load hours	h/a	1 247	3 500	6 000	1 247	3 500	6 000
Heat storage requirements	$kWh_{storage}$ per $kW_{large\text{-}scale\ heat\ pump}$	9[1]	5[2]	0[3]	9[1]	5[2]	0[3]
Electricity supply costs	€/MWh[11]	120	126	140	117	123	139
Purchase cost	€/MWh[11]	32[4]	58[5]	86[6]	32[4]	58[5]	86[6]
Network use charges[7]	€/MWh[11]	62	43	30	62	43	30
Other additional electricity costs[8]	€/MWh[11]	26	25	24	23	22	22
Investment costs	€/kW	See Figure 30					
Maintenance costs[9]	percent	3					
Interest on capital[10]	percent	8					
Estimated service life[9]	years	20					

Sources:
[1] Investment in heat storage per heat output of the large-scale heat pump from scenario T45-Electricity in 2030
[2] Linear interpolation of heat capacity between 1 247 h/a and 6 000 h/a
[3] No investment in a heat storage tank with inflexible operating mode
[4] Electricity price for large-scale heat pumps in the T45-Electricity scenario in 2030, weighted according to heat volume
[5] Linear interpolation of supply costs between 1 247 h/a and 6 000 h/a
[6] Electricity price for inflexible operation of large-scale heat pumps based on immediate demand for heat
[7] Authors' calculation based on price sheets from 20 representative distribution network operators for the year 2023
[8] Electricity tax, levies and concession fee: authors' calculation based on www.netztransparenz.de and taking into account current reforms to the tax and levy system for large-scale heat pumps, see Billerbeck et al. (2023)
[9] Based on VDI guideline 2067
[10] Based on Brunner und Krummenacher (2017)
[11] Refers to MWh electricity

Within the sensitivity analysis, a depreciation term of 20 years is assumed, including the drilling investments. Possible cost advantages from the longevity of geothermal boreholes, as mentioned above, are thus not taken into account in this calculation, but nevertheless play an important role for this form of heat generation.

The combination of large-scale heat pumps with deep geothermal energy as a heat source shows most clearly that for this case, the heat generation costs at low annual utilisation rates are comparatively high, but become increasingly competitive as the utilisation rate increases. With regard to the great potential of deep geothermal energy, two aspects should therefore be emphasised:

- District heating: The direct use of deep geothermal energy, i.e. without large-scale heat pumps, is the first choice for district heating in many cases. A further temperature boost for the source temperature using large-scale heat pumps is often not necessary at all. And if it is, it tends to be feasible with a shallower drilling depth and lower investment costs.
- Process heat: The combination of high-temperature large-scale heat pumps with deep geothermal energy is very well suited to providing process heat at high full load hours. The potential of deep geothermal energy at very high source temperatures should therefore be prioritised and used as far as possible for the decarbonisation of process heat and industrial heat requirements.[13]

With regard to the relevance of electricity supply costs, the analysis confirms that the heat generation costs for heat sources with high COPs (industrial waste heat and deep geothermal energy) are the most robust in the face of fluctuating electricity supply costs. The variation in electricity supply costs is therefore most significant at low COPs. Furthermore, the results of the analysis, in light of the underlying assumptions (see Table 3), also show the significance of the electricity network use charges for future heat generation costs and how important it is for the future network use charge structure to incentivise the operation of large-scale heat pumps in a system-supporting way.

The sensitivity analysis clearly shows the impact of different operating modes on the heat generation costs for different heat source options and thus provides guidance for district heating suppliers in assessing the cost-effectiveness of the various heat sources available.

7.3 BEW funding as a key instrument for the transformation of district heating systems

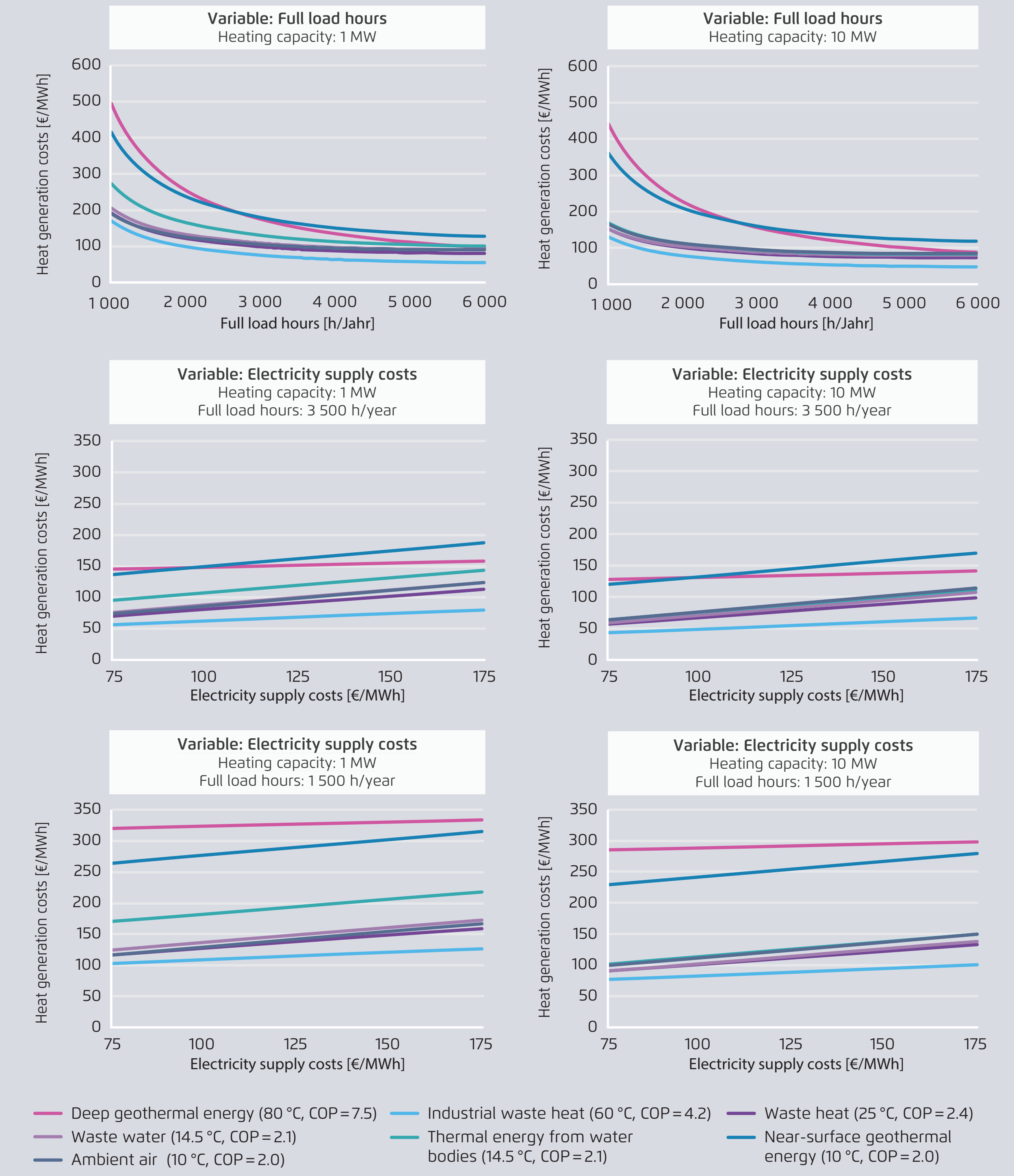
Scope and amount of funding

The aim of the BEW Guideline, which came into force on 15 September 2022, is to contribute to the heat transition by supporting the planning and implementation of energy-efficient heating and cooling networks. The prerequisite for obtaining funding is in most cases a transformation plan that shows how the district heating system can be converted to a greenhouse gas-neutral heating system and that clearly sets out the envisaged transformation path. For existing heating networks, increasing indicative shares of renewable energy and waste heat in heat generation must be specified for the milestone years 2030, 2035 and 2040, to be achieved by means of the measures funded. New networks must submit feasibility studies that include a minimum share of renewable energy and waste heat in heat generation of 75 percent from the outset. The BEW also provides support for the preparation of such transformation and feasibility studies. The Guideline applies to district heating

13 This also requires coordinated site development and local business support which specifically channels business expansion and new business ventures that require high temperatures towards locations with potential for deep geothermal energy.

Unit heat production costs in 2030 for different heat sources with varying full load hours and electricity supply costs for 1 MW and 10 MW heating capacity systems at a sink temperature of 100 °C

Figure 32



Fraunhofer IEG (2023) based on VDI guideline 2067 sheet 1. Calculated without taking subsidies into account.

systems covering more than 16 buildings or more than 100 residential units.

The BEW Guideline, as amended on 1 August 2022, is valid for six years and thus provides a basis for planning new heating networks as well as for network expansion in Germany until 2028 (BAFA 2022b).

The BEW has four distinct modules. The planning of heating and cooling networks in accordance with service phases 1–4 of the Official Scale of Fees for Services for Architects and Engineers (Honorarordnung für Architekten und Ingenieure, HOAI) is funded under Module 1. A distinction is made between new construction and the transformation of existing heating network systems, whereby the preparation of either a feasibility study or a transformation plan is funded. The funding proportion is limited to a maximum of 50 percent, with a total maximum funding sum for Module 1 of 2 million euros per application (BAFA 2022b).

Module 2 provides systemic funding for the construction or transformation of entire heating or cooling systems. To apply for systemic funding (Module 2), a feasibility study or transformation plan must be submitted that meets the requirements of Module 1 (BAFA 2022a).

Module 3 subsidises the investment costs of individual measures for district heating systems, such as central heat generators. If no transformation plan exists yet, at least a target vision of the decarbonised district heating system and a savings forecast must be submitted.

Modules 2 and 3 provide funding for the HOAI service phases 5–8. The maximum total funding sum for both modules is 100 million euros with a maximum funding proportion of 40 percent, and it is limited to the amount of the profitability shortfall (BAFA 2022b).

For large-scale heat pumps and central solar thermal systems supported under Module 2, an additional operating cost subsidy for a period of ten years can be applied for under Module 4. The purpose of this subsidy is to close any remaining profitability shortfall that might arise without this subsidy, assuming that the higher costs cannot be passed on to the heating customers.

The level of the operating cost subsidy is calculated on the basis of certain system parameters, which are specified in the Guideline and the information sheets on the subsidy modules (BAFA 2022b). With funding under Module 3, however, Module 4 can only be applied for if a transformation plan in accordance with the requirements under Module 1 is already in place. This means that if a large-scale heat pump is installed as an individual measure under Module 3 without such a transformation plan, this project will not receive any operating cost support and would thus be at an economic disadvantage compared to projects funded under Module 2. The incentive to use module 3 to integrate large-scale heat pumps more quickly into existing district heating systems is thus reduced. Moreover, drawing up a transformation plan is often very time-consuming and labour-intensive, especially if subsidies have to be applied for in advance. The projects already carried out via the iKWK calls for tenders and the cases described in Chapters 3 and 4 suggest that some district heating suppliers do not need such a transformation plan in order to make a well-informed decision on the installation of a large-scale heat pump that will be viable in the long term. An overly restrictive interpretation of these funding conditions for BEW Module 4 would therefore tend to run counter to the intended acceleration of the expansion of large-scale heat pumps.

An overview of the BEW modules can be found in Figure 33.

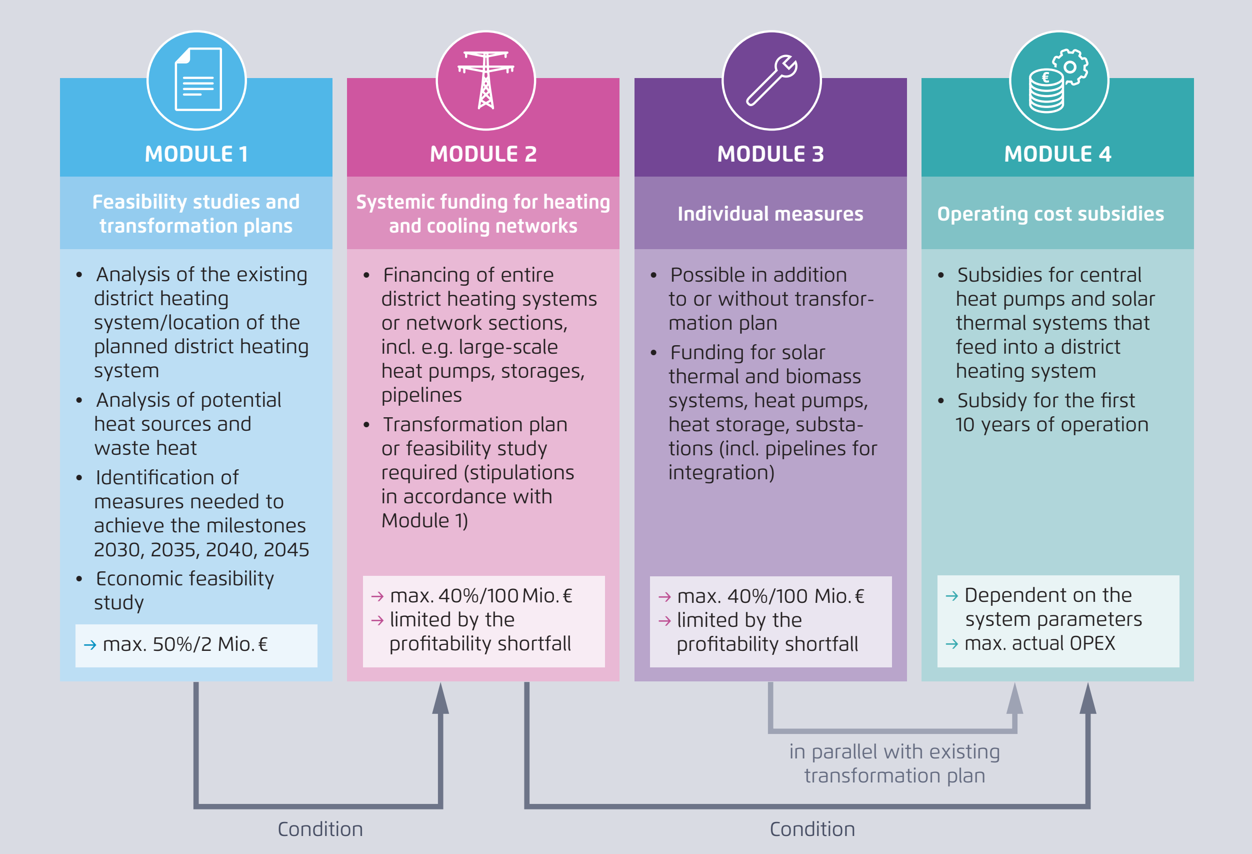
With the operating cost subsidy under Module 4, the BEW provides important incentives for the use of large-scale heat pumps in district heating systems. However, there are some requirements regarding the system parameters of the heat generation used. Until 14 February 2023, an annual performance factor of at least 2.5 was required for large-scale heat pumps for funding under BEW Module 4. The requirement has been criticised as a potential obstacle to the transformation of district heating networks, for example if a reduction of the network flow temperature cannot be carried out in time and a high temperature lift remains necessary (Billerbeck et al. 2023). Furthermore, scenario analyses show that operating cost subsidies are very important, as without them large-scale heat pumps will only achieve lower unit costs than fossil gas systems after 2030 (Billerbeck et al. 2023).

In the new version (1.1) of the information sheet for technical requirements for Modules 1 to 4, the annual performance factor of 2.5 originally specified for systems with an outlet temperature of over 65 °C or for systems with a thermal capacity of over 400 kW has now been replaced by the quality grade, which is calculated proportionally on the basis of the effective COP as specified by the manufacturer (BAFA 2022b).

This amendment has eliminated the disadvantages with respect to operating cost subsidies previously faced by large-scale heat pump projects with low-temperature heat sources or high network flow temperatures and a resulting poorer SCOP value (seasonal COP, equivalent to annual performance factor). The new regulation, by considering the highly location-dependent operating conditions of the heat pump, no longer puts locations with poorer heat sources at a disadvantage in terms of operating cost subsidies compared to locations with better heat sources.

Overview of BEW funding modules

Figure 33



Fraunhofer IEG based on BAFA (2022b)

The need to top up BEW funding

The amount of support from the BEW that has been budgeted up to 2026 is not sufficient to meet the annual demand for new large-scale heat pumps. The influence of the support programme for the market penetration of large-scale heat pumps in the German heating sector has been investigated in a number of scenario analyses. As described in Chapter 3, the expansion requirement of around 4.5 GW per year as calculated in the T45 scenarios would correspond to an investment/market volume of around 2.7–3.6 billion euros per year. The expansion of the distribution network infrastructure in the district heating sector (estimated at around 800 km per year in the T45 scenarios, see Chapter 3.1) requires a further investment of around 0.4–0.8 billion euros per year.

The necessary private sector capital must be mobilised by creating the appropriate framework conditions. In addition to the planning certainty and economic incentives required, this also includes the provision of sufficient budget resources for the funding programmes. In the heating sector, a funding level of 3 billion euros per year has been estimated for the next decade (Gerhardt et al. 2021). Two-thirds of this sum would be allocated to district heating network expansion and one-third to large-scale heat pumps.

However, the total funding volume available under the BEW until 2026 is only 3 billion euros (BEE 2022). Based on the simplified assumption that only measures under Modules 2 and 3 would be funded, and given a maximum funding proportion of 40 percent, this results in a maximum eligible investment volume of 7.5 billion euros over the years 2023 to 2026. The resulting annual eligible investment volume of around 1.9 billion euros per year on average for large-scale heat pumps and heating networks is thus significantly lower than the funding necessary for a rapid market penetration of large-scale heat pumps in the district heating sector, as identified both by this study and by Gerhardt et al. (2021).

7.4 Support under the CHP Act: iKWK calls for tenders and EE bonus

Until the BEW Guideline came into force, support for large-scale heat pumps in Germany was only possible as part of an innovative CHP system (innovative Kraft-Wärme-Kopplung, iKWK) under the CHP Act. Some of the large-scale heat pumps already installed in Germany and currently under construction or planned, as listed in Chapter 2.4 (see Figures 4 and 5), could only be completed thanks to this funding scheme. The CHP Act has thus played a decisive role in ensuring that in 2023 there is already a basic level of knowledge and valuable experience in the installation and operation of large-scale heat pumps in Germany.

Under the CHP Act, iKWK refers to heat generation systems that consist of three thermally interconnected and jointly regulated and controlled components: a CHP system, a heat generator based on renewable energy and a power-to-heat system. The component for the provision of renewable heat must be designed so that at least 30 percent of the reference heat (total heat provision of the CHP system) can be generated as innovative renewable heat in a calendar year (BAFA 2018).

In the absence of a definition of renewable energy in the CHP Act itself, a definition from the Buildings Energy Act (Gebäudeenergiegesetz, GEG) is used. According to Section 3 (2) GEG, geothermal energy, environmental heat and heat from biomass, among others, are considered renewable heat sources. Accordingly, deep and near-surface geothermal systems, electrically driven heat pumps and heat pumps powered by biogas may form a part of systems subsidised under the iKWK.[14] So too can the use of energy from the treated water from sewage treatment plants.[15] The use of waste heat, on the other hand, is excluded from the iKWK scheme (BAFA 2018).

In the iKWK tenders, it is not large-scale heat pumps that are subsidised, but the CHP plant as the core component of an iKWK system. The funding support for iKWK is provided through a surcharge on the price of CHP electricity and exists in two variants. The surcharge

→ is either determined through tenders for iKWK in accordance with § 8b CHP Act.
→ or it consists of the basic surcharge under § 8a CHP Act (tender process for conventional CHP plants) plus a bonus for innovative renewable heat in accordance with § 7a CHP Act (EE-Bonus).

Whereas the iKWK tender processes are for systems with CHP plants in the range of 1-10 MW of electricity output, the EE (Erneuerbare Energie, renewable energy) bonus applies to CHP plants in iKWK systems with an electricity output of 10 MW or more. Simultaneous receipt of both financial support under § 8b CHP Act (iKWK tender process) and the EE bonus is not permitted.

Both types of tender process are regulated in more detail in the ordinance governing tender processes for CHP sytems (KWK-Ausschreibungsverordnung, KWKAusV).[16] In both cases, the plant-specific surcharge amount is determined by the Federal Network Agency (Bundesnetzagentur, BNetzA) on a "pay as bid" basis. The maximum permissible level for iKWK is 12 cents per kWh, which is significantly higher than the maximum level for CHP of 7 cents per kWh (§ 5 No. 2 or 1 KWKAusV). Once the surcharges have been announced, the entire CHP system has to become operational within 54 months.

The surcharge is paid for 45 000 full load hours per iKWK system – in contrast to the 30 000 full load hours for conventional CHP plants. The annual limit for both types of tender is 3 500 full load hours (§ 19 Para. 2 KWKAusV).

This structure of the scheme shows that the iKWK tenders do not subsidise the large-scale heat pumps, but rather that the CHP plant receives a higher CHP bonus for being able to provide heat more flexibly and with lower emissions with the help of a renewable heat generator and a power-to-heat component

Large-scale heat pumps subsidised via the CHP Act can also receive a bonus for innovative renewable heat (the so-called EE bonus). According to the explanatory memorandum to the Act, the support for iKWK systems via the basic surcharge plus the EE bonus is intended "to cover the additional costs of setting up and operating innovative renewable heat generators in innovative CHP systems compared to simple CHP systems". This takes into account that

14 Note: biogas as a drive energy for heat pumps is not considered in this study. From the authors' point of view, the properties of biogas suggest that this energy source should be used sparingly and primarily for energy generation at peak load times and in phases of low electricity feed-in from wind and solar power plants. The optimisation results of the T45 scenarios support this approach (see Chapter 3.1).

15 § Section 2 no. 9a CHP Act. See also: BT-Drs. 19/17342 of 24 February 2020, p. 158.

16 For CHP systems with an electrical output between 500 kW and 50 MW, the level of the surcharge is determined in a tendering process. A distinction is made between tenders for CHP systems under § 8a CHP Act and tenders for iKWK systems under § 8b CHP Act. It is assumed that CHP plants that could be combined with a large-scale heat pump in an iKWK system according to the described specifications are usually in the capacity range for which tenders are required.

these additional costs increase in line with an increasing proportion of renewable heat and that CHP heat production decreases accordingly.[17]

The amount of the EE bonus is fixed by law and varies, depending on the share of renewable heat, between 0.4 cents per kWh for at least 5 percent renewable heat and 7.0 cents per kWh for at least 50 percent renewable heat (§ 7a para. 1 CHP Act).

The main criteria for the iKWK support and the EE bonus under the CHP Act are placed in the wider context of this study below (see Table 4).

7.5 The need for further refinement of the CHP Act

Large-scale heat pump projects are currently characterised by extensive appraisal and decision-making processes (see also Chapter 8) and by limited human and financial resources among all stakeholders. This fact is exacerbated by the fact that large-scale heat pumps in district heating systems are currently eligible for support under both the BEW Guideline and the CHP Act: the existence of different support options with different funding pots, funding quotas and assessment criteria is unnecessary and inefficient – both from the point of view of the companies applying for support and from that of the federal government as the provider.

The CHP Act was of crucial importance for the promotion of highly efficient and flexible cogeneration. However, in the current phase of the energy transition – in which the system-supporting operation of large-scale heat pumps is becoming increasingly important – it is essential to ensure that support under the CHP Act is also fully in line with Germany's climate targets and policy measures.

17 Ibid., p. 161.

It is therefore urgently necessary that the financial support landscape for the heat transition also – or perhaps especially – sets clear priorities and thereby both creates planning certainty and reduces complexity. Achieving this is made more difficult by the continued availability of the iKWK support option for large-scale heat pumps (see Chapters 7.4 and 8). For example, system configurations in which the waste heat from a CHP plant based on fossil gas acts as the heat source for a large-scale heat pump are also eligible for support via the iKWK calls for tenders. There is a risk that such incentive schemes could lead to fossil CHP plants remaining in operation longer than necessary and could thus slow down the transformation of district heating systems.

A recent study commissioned by the Federal Environment Agency, for example, also concludes that the CHP Act "sets perverse incentives for the transformation of district heating systems, which even the carbon price is unable to compensate for" (UBA 2023a).

Supporting the expansion of renewable heat and the decarbonisation of district heating systems – including greater use of large-scale heat pumps in district heating systems – is now being addressed much more effectively by the BEW Guideline and the upcoming amendment to the GEG (Buildings Energy Act) than by the CHP Act (see UBA 2023a). The support for iKWK under the CHP Act is therefore no longer necessary in its current form and may even be counterproductive in some cases. It is also rarely a viable option for new district heating systems since the BEW Guideline came into force, unless the required share of renewable heat can be covered to a significant extent from unavoidable waste heat and/or from renewable fuels in CHP plants.

It is also important that investments in CHP plants currently still eligible for support under the CHP Act do not create any fossil fuel lock-in effects that could further delay decarbonisation. An expansion of new fossil gas CHP plants promoted by the CHP Act should therefore be avoided at all costs. Instead, the focus of the CHP Act could be placed on the necessary flexibilisation of the CHP plant stock and on the installation of highly flexible CHP capacities based on biomass, substitute fuels and green hydrogen, for which there is a great need by 2045 (see T45 scenarios in Chapter 3).

Against this background, it is therefore necessary to examine how the CHP Act can, with appropriate transition periods, be swiftly reformed – for example towards a sector coupling law – to reflect the role of CHP in the energy system up to the years 2030 and 2045.

Support under iKWK and the roll-out of large-scale heat pumps — Table 4

<table>
<tr><th>Criteria for iKWK and the EE bonus according to the KWKG</th><th>Significance in the context of this study</th></tr>
<tr><td>Share of innovative renewable heat at least 30 percent in iKWK systems (up to 50 percent with the EE bonus)</td><td rowspan="3">The KWKG support must be used to meet the requirements of the Climate Protection Act and to achieve the BEW targets. New district heating systems must have at least a 75 percent share of renewables or waste heat in heat generation, and existing networks must follow a clear path to greenhouse gas neutrality by 2045. The T45 scenarios provide guidance for economically efficient reduction paths (see Chapter 3).
If large-scale heat pumps are operated flexibly and in a way that supports the system, they very quickly achieve very low CO_2 emission factors and make a major contribution to decarbonisation (see Chapter 3.2)</td></tr>
<tr><td>Large-scale heat pumps must contribute to greenhouse gas reduction and the use of renewable energy in the heat supply</td></tr>
<tr><td>Use in existing or new district heating systems*</td></tr>
<tr><td>Enabling greater flexibility** and temporal decoupling of heat and electricity generation (together with the power-to-heat component)</td><td>The flexible and system-supporting use of large-scale heat pumps is a key factor for a successful energy transition (see Chapter 3.2)</td></tr>
<tr><td>Innovative heat generators from renewable energy must achieve an annual performance factor of at least 1.25***</td><td>Meeting this criterion is not a problem for large-scale heat pumps (see Chapter 6.1)</td></tr>
<tr><td>The CHP component should be a new or modernised plant</td><td>According to the T45 scenarios, CHP plants will increasingly have to take on the role of peak load and backup capacities for the electricity and heat sectors, primarily burning biomass, substitute fuels or green hydrogen (see Chapter 3).
The support under the CHP Act should take these findings into account.</td></tr>
</table>

Fraunhofer IEG (2023)
* BT-Drs. 18/10209 of 7/11/2016, page 3. (Publications of the federal German parliament) ** According to the explanatory memorandum to the Act, the aim is to ensure that CHP systems "can react flexibly in the electricity market and in redispatch", and that they "do not lead to a minimum generation and do not displace renewable energy sources in electricity production". See: BT-Drs. 619/16 of 20/10/2016, page 4. (Publications of the federal German parliament) *** § 2 Nr. 12 lit. a) KWKAusV.

8 Planning and development of large-scale heat pump projects for district heating: the perspective of the district heating suppliers

8.1 Competent municipal utilities and district heating suppliers as key players

For the market ramp-up of large-scale heat pumps in the district heating sector, municipal utilities and district heating suppliers hold a central position alongside manufacturers. Therefore, the perspective of these stakeholder groups is of central importance in identifying the current challenges and influencing factors crucial for an accelerated roll-out of large-scale heat pumps in Germany.

The T45 scenarios show that the expansion of (district) heating systems is a prerequisite for a successful heat transition in Germany. However, the decarbonisation of district heating has not progressed to the extent necessary in recent years (see Chapter 2.1). At the same time, district heating suppliers strived to increase the efficiency of their district heating systems through measures aimed at network densification and temperature reduction and to reduce the primary energy factor of their heat supply. In the context of the energy industry conditions and energy policy at the time, the latter aim was achieved primarily by replacing coal and heating oil with highly efficient and flexible fossil gas CHP plants.

The continuing and growing climate crisis, the fossil energy price crisis in Germany and Europe and the associated efforts to phase out fossil energies as quickly as possible mean that a large number of decisive political decisions and transformation measures must now be implemented simultaneously. In this context, increasing attention is being paid to district heating systems as an efficient way to use renewable energy.

All municipal utilities and district heating suppliers are therefore currently faced with the question of how they can fully decarbonise their district heating systems as efficiently as possible by 2045 at the latest. The idea of converting to large-scale heat pumps is often still viewed with scepticism due to a lack of relevant data and experience.

The approach adopted in this study: learning from the experience of the pioneers in Germany

The information below – especially that on approximate processing times, current challenges and important success factors – and how it is evaluated in the context of this study is largely based on up-to-date data provided by professionals in the field.

To this end, as a first step in the course of compiling this study, Fraunhofer IEG analysed the publicly available information on large-scale heat pump projects currently either in operation or else under construction, in planning or announced in Germany (see Chapter 2.4).

As a second step, Fraunhofer IEG used this information to contact the investors, operators and planners of around 20 projects, as well as the AGFW. In addition to verifying the key techno-economic data from the projects, this enabled a better understanding of the perspective of the pioneers in the German large-scale heat pump market and to enrich the present study by providing first-hand qualitative information on the success factors and challenges involved in carrying out the projects. Appendix A.1 describes projects that have played a pioneering role of this kind.

As a third step, an anonymised online survey on the issues covered by this study was carried out in February 2023 and analysed. For this purpose, in addition to the AGFW, representatives from 32 municipal utilities, district heating suppliers, the housing industry and local authorities were contacted who have already gained experience with large-scale heat pump projects or are currently working on this topic.

As a fourth step, a stakeholder workshop was held in March 2023 with 26 participants from the stakeholder groups mentioned above together with a planning and engineering firm active in the field of large-scale heat pump projects. The participants in this event can mostly be classified as pioneers. This means that the perceptions and insights identified in this exercise do not represent the entire district heating sector, but they are nevertheless helpful for assessing the success factors and challenges for the roll-out of large-scale heat pumps.

Challenges and action required from the point of view of district heating suppliers

Current challenges are mainly related to licensing procedures, heat sources, heat sinks and technology. The survey confirms that the approval process, with its unknown variables and associated workload and time requirements, represents a particular challenge for municipal utilities and district heating suppliers. The choice of technology and refrigerants, as well as the long delivery times and short price fixing agreements for the large-scale heat pumps, also pose challenges for the stakeholders surveyed. The difficulty of obtaining sufficient renewable electricity on competitive terms for the operation of the large-scale heat pumps was also repeatedly mentioned (connection to the network, price of electricity).

In addition, challenges mentioned several times in varying degrees are related to the heat source (difficulty of exploitation, output, temperature, willingness of potential waste heat suppliers to cooperate) and the heat sink (temperature of the district heating network).

The most frequently cited success factors for large-scale heat pump projects were early and close cooperation with (approval) authorities and stakeholder management. The district heating suppliers are therefore hopeful that measures will be taken to accelerate the planning and approval processes for their investment projects similar to those taken for the new LNG terminals in Germany in 2022 and to those already approved in the meantime for wind energy and solar plant expansion. This argument is supported by the fact that the transformation of district heating systems is also of overriding interest to the general public and that large-scale heat pumps tend to be low-conflict infrastructure measures compared to conventional centralised heat generation systems.[18]

The quality of the heat source (location-dependent and difficult to influence) and the financial support options (subject to political influence) were also mentioned repeatedly.

The challenge of lowering the temperature in existing district heating systems is not an obstacle to the roll-out of large-scale heat pumps. Even at network temperatures common today, large-scale heat pumps can already achieve good to very good COPs, depending on the heat source (see Chapter 4). Nevertheless, for efficiency reasons, it is still important to gradually reduce the flow and return temperatures in district heating networks. However, according to the participants interviewed, this is proving difficult. In response to the questions, "What do you consider to be the realistic temperature reduction potential in the district heating network by 2045? What challenges/problems are involved?", the following illustrative issues were identified by 13 participants (excerpt):

18 This statement only applies to a limited extent to medium-deep and deep geothermal energy or to the use of surface water bodies as heat sources.

- → Considerable financial and personnel costs for property owners and district heating system operators for the necessary conversion of customers' heating appliances connected to the existing district heating networks.
- → Expanding networks and thus a higher heat demand preventing temperature reduction to some degree.
- → The measures needed to optimise the heating network as well as the network regulation to provide the necessary transport capacities and temperature differences between the flow and return.

Nevertheless, the survey participants assume that temperature reductions of at least 5 kelvins and up to 30 kelvins by 2045 are possible in their existing networks over the next twenty years or so. Thus, the requirements of the heat sinks and the growing technical capabilities of large heat pumps will continue to converge in the coming years.

However, the fact that the current strategies for configuring and integrating large-scale heat pumps into existing heating networks are still very different is shown by the answers to the question of how the differing speeds of building renovation programmes and network temperature reductions are to be taken into account when planning and configuring large-scale heat pumps.

For the complex trade-offs and decision-making processes involved in large-scale heat pump projects, district heating suppliers can benefit from the experience gained with CHP plants. The municipal utilities and district heating suppliers who assess and take forward large-scale heat pump projects are confronted with numerous both new and familiar issues and (trade-off) decisions during the planning and implementation phases. Some of these are already familiar to them from investments in CHP plants, others are more specific to the technology or heat source. Table 9 in Appendix A.5 provides an overview of the most important issues.

8.2 Potential for process acceleration from the perspective of district heating suppliers

Process steps involved in large-scale heat pump projects for district heating suppliers

In order to successfully complete a large-scale heat pump project, district heating utilities must

- → define the transformation targets for their heating networks (= heat sinks) in terms of time and decarbonisation progress (see Chapter 3),
- → identify and evaluate the potential heat sources available (see Chapters 4 and 7),
- → devise measures to tap the heat sources and to integrate the large-scale heat pumps into their heat generation portfolio and district heating system (see Chapter 5),
- → ensure the necessary finance for the measures is available and examine the support options under the BEW Guideline and the CHP Act (see Chapter 7),
- → plan and configure the technical design of the large-scale heat pumps including all peripheral elements (buildings, heat storage, connection to the electricity and district heating networks, expansion of the heating pipeline system, etc.) (see Chapters 5 and 6),
- → maintain close and regular contact with the local authority, heating customers, licensing authorities and the general public from the beginning to the end of the project,
- → prepare and constructively assist with the approval process,
- → run a competitive tendering process for the supply and construction of the large-scale heat pump system,
- → monitor, supervise and approve the execution of the construction work and
- → operate the large-scale heat pumps economically and in a system-supporting manner for a period of around 20 years (see Chapter 7).

Figure 34 shows the main tasks involved in a large-scale heat pump project and their chronological sequence based on the service phases of the HOAI.

The complexity and the time requirements of the work phases shown in Figure 34 depend in each case on the heat sink and heat source, the location, the performance and the design of the large-scale heat pumps, the delivery times for the systems, and the scale and complexity of the other project-related construction work. Depending on the project, the time required from the start of the initial assessment to the beginning of operations can be around four to six years under today's framework conditions.[19]

The "quick" projects usually benefit from several of the following features:

- → minimal resource requirement for the basic evaluation because of existing targets, heating strategy and/or transformation planning, as well as rapid processing of the funding applications,
- → favourable site conditions, such as easy access to the heat source, existing power plant on-site, short distances between heat source and sink, and sufficient electricity network connections,
- → small capacity large-scale heat pumps and little need for peripheral construction measures – and consequently potentially also no need for an EU-wide tendering process,[20]
- → good cooperation with waste heat suppliers, the local authority administration and with licensing authorities, rapid approval procedure,
- → no shortage of skilled workers among project developers, authorities and construction companies as well as short delivery times for large-scale heat pumps and associated components and
- → experience gained from comparable projects.

Besides the usual learning processes for all actors involved, there are several levers that can further speed up the completion of the project.

Process acceleration potential from the perspective of district heating suppliers

Strengthening human resources across the different sectors involved, in particular through:

- → eliminating the shortage of skilled workers among manufacturers, energy suppliers, project planning agencies and contractors, construction companies, licensing authorities and funders, for example through
  - a clear prioritisation of the tasks that are relevant to transformation, climate protection and security of supply in the internal allocation of these actors' human and financial resources (if necessary, through indirect incentives and obligations under climate change legislation),
  - recognising the importance of this value chain for sustainable long-term employment and prosperity in Germany and
  - more education and training programmes for this sector as well as re-training programmes for sectors with comparable skills requirements (for example, the automotive sector and the internal combustion engine sector).
- → increased digitalisation of processes and of cross-sectoral cooperation.

19 Not taking into account any additional investments that may be required in the expansion and development of the district heating network.

20 According to EU procurement law, construction contracts above a certain contract value must be put out to tender throughout the EU. This increases competition and offers the opportunity to benefit from the potentially superior experience of foreign bidders, but also lengthens the duration of the process. In 2023, this threshold value is 5.38 million euros (net). Depending on the heat source and the design of the large-scale heat pump system, this applies to projects in the range from just under 2 MW (for deep geothermal energy) to around 9 MW (for waste-water heat pumps, see Chapter 7.2).

Reducing the time needed for the initial assessment phase, especially through:

- clearer political guidelines and regulatory frameworks that simplify the decision-making processes for large-scale heat pump technology,
- increasing awareness regarding the results of the T45 scenarios, the technological state of the art of large-scale heat pumps, and best-practice examples from Germany and Europe,

Phases of a large-scale heat pump project showing the most important tasks with approximate duration in months — Figure 34

Fraunhofer IEG (2023) based on information on current and completed projects

- standardised large-scale heat pump projects, greater modularity, and more knowledge regarding the optimal areas of application for different large-scale heat pump products,
- more digital transparency regarding potential heat sources available throughout Germany and existing heat demand and energy infrastructure (heat mapping and digital twins),
- speeding up the processing of funding applications and further simplifying the access to funding for project implementation (for example, BEW operating cost support also for individual measures under Module 3).

Speeding up the entire planning and approval process by:
- involving construction project managers or general contractors,
- providing (practical) handbooks[21] with specific information on the use of different heat sources and large-scale heat pump technologies for investors, planners and relevant authorities,
- enshrining into law at both federal and state level that measures to decarbonise district heating systems are of "overriding public interest", including aligning laws which currently are to some degree in conflict (e.g. spatial planning, land law, water law, Federal Mining Act, building code, environmental impact assessment),
- extending the accelerated licensing measures for large-scale heat pumps introduced under the 18-month EU Emergency Regulation which came into force in December 2022,[22] and
- quickly introducing mandatory municipal heat planning and designating preferential areas under land use planning regulations. The transformation of district heating systems can be accelerated if, in future, every (inner-city) civil engineering measure is checked in advance to see whether proactive measures can be taken for ensuring in advance that heat sources can be tapped or that heating pipelines can be laid.

Shortening the tendering process through:
- improved tender documents, more competition among bidders and better offers as a result of the learning process and the improvements in the preceding work phases,
- incremental planning of several smaller single plants/projects instead of one large project, or division into different batches; and
- a review of the legal options for shortening the tendering process for "pilot" measures or measures of "overriding public interest".

Reducing delivery times for large-scale heat pumps and their components and accelerating the construction phase through:
- greater political planning certainty for manufacturers so that they can expand their production capacities at an early stage and take precautions against supply bottlenecks,
- further standardisation of the components of large-scale heat pumps in the 1–10 MW range, which would enable modular use across a wider range of applications, and
- the introduction of state guarantees (sureties) to cover the production risks for manufacturers during the market ramp-up phase, when increasing demand has not yet been translated into orders.[23]

21 The AGFW has already produced such a practice handbook for large-scale heat pumps. It is available here: https://www.agfw.de/praxisleitfaeden (as of June 2020; last accessed on 28 March 2023).

22 Council Regulation (EU) 2022/2577 of 22 December 2022 laying down a framework to accelerate the deployment of renewable energy (OJ L 335, 29 December 2022, p. 36-44) states in paragraph 1, Article 7 on accelerating the development of the use of heat pumps: „The permit-granting process for the installation of heat pumps below 50 MW electrical capacity shall not exceed 1 month, whilst in the case of ground source heat pumps it shall not exceed 3 months".

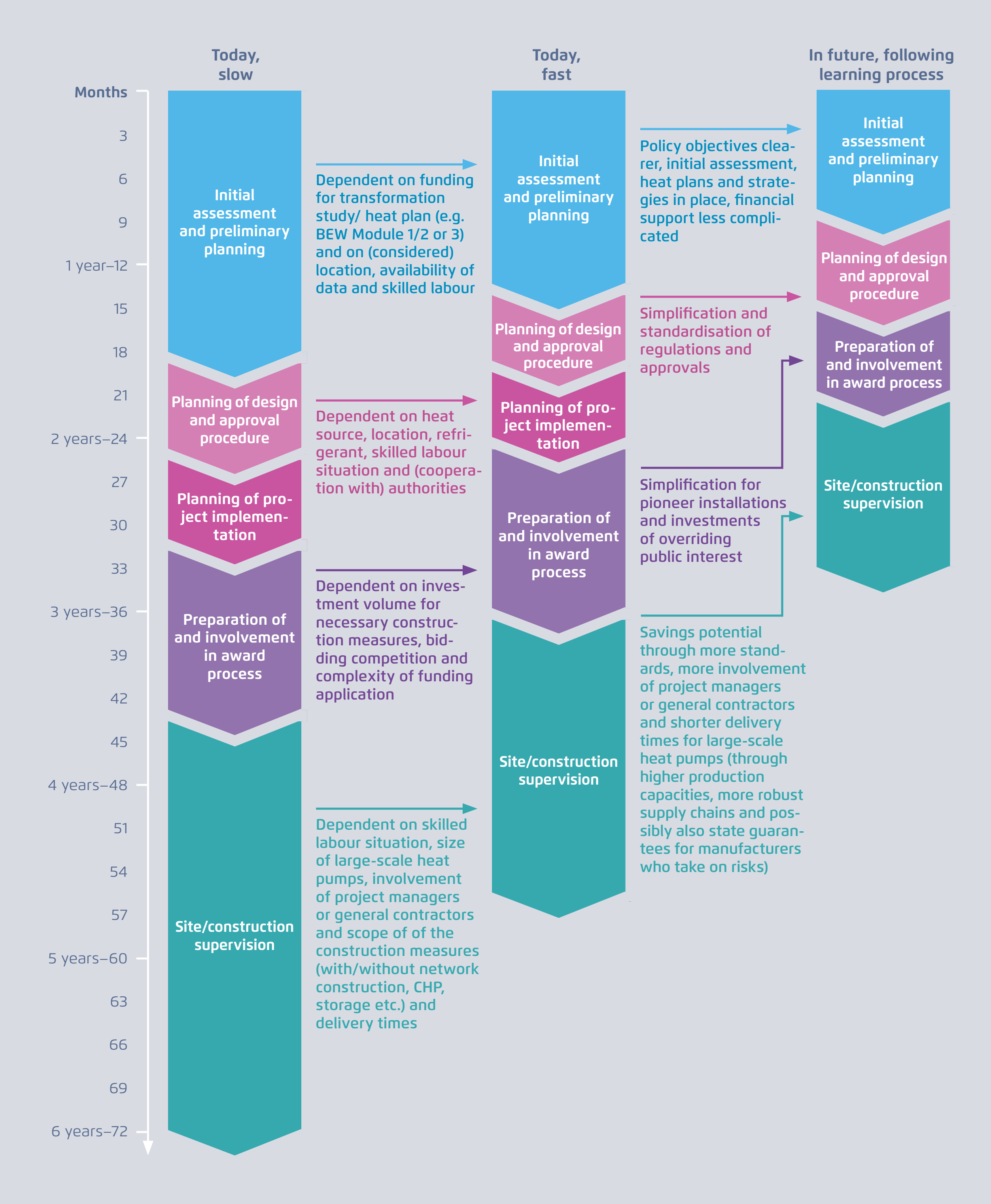
23 This instrument was proposed, for example, in the „Draft Industrial Policy Strategy for Renewable Energy and Electricity Networks" (dena 2022), based on the findings of the „Stakeholder Dialogue on Industrial Production Capacities for the Energy Transition (StiPE)",

If these levers are operated, project durations of around three years for smaller large-scale heat pump projects appear to be possible (see Figure 35).

What is certain is that the market for large-scale heat pump projects in Germany is at the beginning of a steep learning curve with regard to their production, planning, installation and operation. Planning certainty and accelerated and simplified approval procedures, along with the build-up of manufacturers' production capacities, are crucial to a rapid roll-out.

with reference to the expansion of onshore wind energy. Such guarantees are intended to enable manufacturers to start their ordering and production processes well in advance of possible incoming orders by having the state indemnify manufacturers against the associated financial risks.

Potential for speeding up the planning, approval and completion of large-scale heat pump projects Figure 35



Fraunhofer IEG (2023) based on data from practical experience and the applicable framework conditions as well as the areas of action identified

9 Fields of action toaccelerate the roll-out of large-scale heat pumps in district heating

By 2045, an average of well over 300 individual projects with a new large-scale heat pump capacity of more than 4 GW and 800 km of new pipelines will have to be planned, financed and constructed every year. This is a task for the whole of society that requires clear prioritisation from politicians and a high level of innovation and efficiency from manufacturers and district heating network operators. It is crucial that a cleverly phased mix of price signals, support measures and regulatory requirements ensures a rapid ramp-up, while at the same time allowing supply chains and implementation capacities to grow without problematic bottlenecks.

The necessary measures can be categorised into three core areas for action. First, a coherent overall framework is required that combines a clear strategic vision with consistent price signals for the use of energy carriers and infrastructures. Secondly, the potential for innovation, scaling and cost reduction must be exploited consistently and quickly by manufacturers. Thirdly, the transformation of district heating systems must be accelerated on a structural level through a reform of the support framework and a package of measures to simplify its implementation. The specific measures to be taken within these three areas of action are described in more detail below.

9.1 Overall framework: clear targets, efficient energy prices, and revised network use charges

Manufacturers and end-users must be able to rely on the ramp-up process, market conditions must be able to support the ramp-up through efficient price signals. Only in this way can the potential of large-scale heat pumps and district heating systems for a climate-neutral energy supply be quickly and extensively exploited. In addition to a clearly articulated, credible target vision for the ramp-up path, the relative prices of different energy sources and the charges for the use of infrastructure are the most important control levers in this context.

In order to create clarity about the goals for manufacturers and operators, a stakeholder process at federal level (a large-scale heat pump summit) should formulate a long-term goal with ambitious interim targets. This goal must outline a market ramp-up that is as credible as it is ambitious, and must be underpinned by effective policy instruments (see the points below). If possible, comparable dialogue processes should take place at state and local authority levels.

The economic viability of the large-scale heat pumps currently either in planning or operation depends crucially on the ratio of electricity to gas prices – at present, taxes, levies and surcharges create perverse incentives. Currently, heat pumps are in competition with fossil gas plants in new construction projects and, in the foreseeable future, also in operation. In this context, carbon pricing is of crucial importance. Currently, heat pumps – whether stand-alone or connected to heating networks – face an important disadvantage: their electricity supplies on the wholesale market are exposed to the high carbon prices in the European Emissions Trading Scheme (ETS).[24] When fossil gas is burned in plants and sectors that are not

24 The reason why electricity procurement is (indirectly) burdened with ETS costs is because of how prices are set on the electricity market: the price is determined by so-called marginal power plants, which are generally still fossil-fuelled today.

part of the ETS, on the other hand, only the significantly lower price under the German BEHG (Brennstoffemissionshandelsgesetz, Fuel Emissions Trading Act) is charged.

The new emissions trading system (ETS2) planned at the European level for the buildings and transport sectors or an increase in prices under the BEHG could correct the current distortion. A price floor that increases over time could provide the necessary investment and planning security. In contrast, a possible price cap under the ETS2, which is also currently under discussion, would again limit the effectiveness of this instrument, weaken investment incentives for large-scale heat pumps and further jeopardise the achievement of the climate targets for the heating sector (MCC 2023). Furthermore, electricity continues to be subject to higher taxes, levies and surcharges than gas. A further reduction of these perverse incentives, for example through reducing the electricity tax to the European minimum level, could remedy this situation and thus create a level playing field.

The introduction of network use charges that vary according to time is essential to ensure that heat pumps use renewable electricity in a way that supports the system and protects the network. Germany is one of the few countries in Europe where there are still no time-variable network use charges (Acer, 2023). In addition, charges for larger customers (with load profile metering) are assessed exclusively on the basis of the customer's annual peak load – regardless of whether or not the network was actually being used at that point in time. This is a crucial obstacle to flexibility, as the operation of heat pumps under these circumstances cannot be optimised to suit the concurrent state of the network. For example, a particularly high utilisation makes systemic sense when there is strong local renewable electricity production, and ought to be possible at a correspondingly favourable price.

9.2 Large-scale heat pumps: rapid cost reduction, further performance enhancements and increased production capacities

Large-scale heat pumps have considerable potential for performance enhancements and simultaneous cost reductions – manufacturing companies must consistently exploit this potential and should be strategically supported in doing so. The basic technical principle and the individual components of heat pumps have been known and commercially available for decades. Especially in Northern Europe, large-scale heat pumps have been in use for many years already and have proven themselves in operation. With regard to customer needs, which will change dramatically with the imminent expansion of the market volume in district heating systems, the industrial and scalable mass production of efficient large-scale heat pumps is still in its infancy due to insufficient demand. An anticipatory and rapid expansion of supply is therefore essential to avoid shortages or sharp cost increases in large-scale heat pumps when demand picks up quickly.

The focus of the market ramp-up should be on lower costs and higher unit numbers through standardisation and modularisation in the power range up to 10 MW. Standardised products are currently only available on the market for the output range up to 1 MW. An expansion of standardisation to cover output ranges up to 10 MW should be pursued as a matter of priority. Firstly, the unit investment costs (euros per kW) can be reduced through the use of larger production systems. Secondly, standardisation enables higher unit numbers and economies of scale in manufacturing and project implementation. Beyond a size of 10 MW, highly customised solutions will remain necessary for the foreseeable future. For the market ramp-up, a focus on multiple projects in this medium output range – instead of fewer projects with outputs significantly above 10 MW – can therefore be advantageous, especially in the next few years.

The further development of compressors holds considerable potential for boosting the performance of large-scale heat pumps and for the use of natural refrigerants. Compressors are the technical heart of heat pumps. They account for the largest proportion of the electricity consumption of heat pumps and have a major influence on their technical performance and operating efficiency. Compressors must also be adapted to new refrigerants or to refrigerants that have only recently been introduced into this field. Technical innovations in compressors and refrigerants enable performance improvements with regard to three key criteria. Firstly, higher target temperatures and temperature lifts can be achieved. Secondly, increases in efficiency are possible, i.e. an improvement in the COP. Thirdly, greater flexibility can be achieved by enabling operation across a wider thermal output range and with faster load changes and start-up and shutdown sequences. This facilitates a system-supporting mode of operation.

With regard to refrigerants, the question of whether the use of perfluorinated and polyfluorinated alkyl compounds (PFAS) is permissible should be clarified quickly at European level. For existing manufacturing facilities or those already under construction that are designed to use refrigerants containing PFAS, grandfathering should be considered.

Building up industrial manufacturing capacity should be a focus of industrial policy. Only with a significant expansion of global and European manufacturing capacity can the potential of large-scale heat pumps be fully exploited. In the context of a stronger emphasis on resilient supply chains, the expansion of European manufacturing capacity in particular has a central role to play. Alongside photovoltaics, wind turbines, electrolysers and batteries, heat pumps are among those decarbonisation technologies that the European Commission has identified as being of strategic significance.[25] Against this background, the establishment of new production capacity in Europe, combined with instruments to ensure long-term demand, should be a priority.

9.3 District heating: a streamlined funding landscape, mandatory planning and simplified implementation

The extension and new construction of district heating systems, along with their upgrading, are key drivers for the market ramp-up of large-scale heat pumps – such measures must therefore be simple, quick and economically attractive to carry out. In order to achieve this goal, adjustments are necessary in three areas. Firstly, financial support systems must be improved or better coordinated. In particular, the existence of parallel subsidy schemes under the existing CHP Act and the new BEW currently leads to perverse incentives. Secondly, municipal heat planning must be made mandatory and developed into integrated planning for the energy system (a local energy distribution strategy). This will identify the priority areas for networked heat supply. Thirdly, the time required for projects to be implemented must be halved from currently up to six years to around three years through a package of modifications and simplifications to the approval and implementation processes.[26]

Perverse incentives created by the CHP Act and the BEW Guideline must be eliminated through simplification of the financial support landscape. Alongside the BEW Guideline, the old support system for CHP continues to exist under the CHP Act. This currently leads to significant perverse incentives, in particular to designs for heat pumps that are too small and to the continuous operation of CHP plants and heat pumps, which is highly problematic for the electricity system

25 European Commission (2023): Green Deal Industrial Plan for the Net-Zero Age

26 These are average times. The actual duration of projects depends on many factors, including the size of the plant and the scope of the construction work.

as a whole. This should be corrected via a fundamental reform of the CHP Act.

The financial resources of the BEW must be increased. The entry into force of the BEW on 15 September 2022, several years late, marked a decisive step towards the transformation of district heating systems to a climate-neutral provision based on renewable energy. Given the necessity of a market ramp-up of large-scale heat pumps, as shown in this study, the financial resources of 3 billion euros currently allocated until 2026 are insufficient. Additional funding of around 1.8–3.9 billion euros would be required by 2026 just for the annual expansion needed for large-scale heat pumps with a thermal output of around 4.5 GW (incl. heat storage) and the construction of around 800 km of new heating pipelines (cf. Chapter 7.3). However, this very rough calculation does not take into account either the operating cost subsidies under BEW Module 4 or the expansion of solar thermal energy and deep geothermal energy – so the funding shortfall is significantly larger. Against this background, an analysis conducted by Agora Energiewende (2022) recommended increasing the funding by a further 8 billion euros to a total of 11 billion euros.[27] The transformation of district heating systems must also be accompanied by the renovation of the buildings and heat transfer stations connected to these networks. This must be taken into account in the further refinement of the BEW Guideline.

The operating cost subsidy for individual measures under BEW should not be interpreted in an overly restrictive way. Large-scale heat pump projects implemented as individual measures under Module 3 of the BEW Guideline and contributing to the accelerated market ramp-up should, as far as possible, not have any economic disadvantages compared to large-scale heat pumps supported as part of a systemic measure under Module 2. This means that the requirements for entitlement to operating cost support under Module 4 – i.e. the existence of a transformation plan that meets the requirements of Module 1 – should not be interpreted too restrictively for individual measures under the BEW.

For deep geothermal energy, exploration activities and the hedging of exploration risk are important. There are still gaps in the mapping of the deep geothermal energy potential in Germany. Furthermore, an instrument for hedging the exploration risk for wells is lacking. Measures are therefore needed to finance an exploration programme and a mechanism for hedging the exploration risk.

Municipal heat planning must be introduced on a mandatory basis and further developed into integrated energy infrastructure planning (a local energy distribution strategy). The success of the heat transition depends on its implementation on the ground – and for this, nationwide municipal heat planning is crucial. Binding regulations must be established at the federal level so that reliable and comparable heat plans are created in all local authorities – especially with regard to the achievement of climate targets and the limited use of hydrogen and biomass. In particular, local authorities need support in obtaining data (legal clarification) and for personnel. To ensure that the heat plans can also be implemented, they must become legally binding. In addition, municipal heat planning should be further developed into a local energy distribution strategy that enables the coordinated planning and installation of electricity, gas, hydrogen and district heating networks.

27 A similar order of magnitude is cited by Gerhardt et al. (2021), who arrive at a necessary funding volume of 3 billion euros per year, of which two-thirds is for district heating network expansion and one-third for large-scale heat pumps.

Large-scale heat pump projects can be significantly speeded up through leaner planning, simplified approval processes and stronger implementation capacities. Shortening project duration from up to six years at present to around three years requires a bundle of individual measures each of which can only make a limited contribution on its own, but which have a major impact as part of an overall package. These are presented in detail in Chapter 8; the most important individual measures are briefly listed again below:

- → **The designation of the expansion of climate-neutral district heating systems as a "measure of overriding public interest".** In parallel with the expansion of renewable energy and the electricity grids, such a legal status would help to ensure that trade-off decisions that favour district heating systems would be made more quickly and reliably.
- → **Consolidation of the measures to accelerate approval procedures for large-scale heat pumps** introduced within the framework of the EU Emergency Regulation, which came into force in December 2022 and is limited to 18 months.[28]
- → Simplification of approval procedures for **the use of surface water and wastewater as a heat source.** In low-risk and standardised projects, testing and verification requirements that are not absolutely necessary can be omitted, enabling faster project implementation without compromising water protection.
- → **Electricity grid expansion and faster connections to the grid for heat pumps.** Depending on the region, one of the more than 800 different electricity grid operators is responsible for the connection of heat pumps to the grid in Germany. These each have their own grid connection conditions, application procedures and testing methods. This leads to considerable additional administrative work and, in some cases, long waiting times for a connection. Clear specifications for connection requirements and deadlines are becoming all the more important as the market ramp-up of heat pumps and electromobility progresses.
- → **Providing practical guides** for investors, approval authorities and planners in order to make best practice experience readily available and to make the approval and planning processes more efficient.
- → **Draw up comprehensive registers of heat sources and their potentials and make them publicly available.** Making this data available quickly, digitally and unbureaucratically contributes significantly to speeding up projects and is already common practice in other European countries.
- → **An obligation to either use or provide access to industrial waste heat after meeting one's own needs.** Legal clarification can avoid time-consuming negotiations over individual projects and enable heat potentials to be harnessed more quickly and cost-effectively.
- → **Speeding up (EU) tendering procedures for large-scale heat pump projects in the market ramp-up phase.** To ensure eligibility for funding, project components and services must be put out to tender across Europe. Switching to a simplified procedure – while at the same time ensuring cost-effective procurement – can shorten project durations.
- → **Reducing the shortage of skilled workers** among manufacturers, energy suppliers, project planning offices and contractors, construction companies, approval authorities and funding providers. What is needed, for example, is a clear prioritisation of jobs relevant to transformation, climate protection and security of supply, better education and training programmes, and retraining opportunities in sectors with comparable skills requirements (for example, the automotive sector and the internal combustion engine sector).

28 Council Regulation (EU) 2022/2577 of 22 December 2022 establishing a framework for the accelerated development of the use of renewable energy (OJ L 335, 29 December 2022, p. 36-44) states in paragraph 1, Article 7 on accelerating the development of the use of heat pumps that „the permit-granting process for the installation of heat pumps below 50 MW electrical capacity shall not exceed 1 month, whilst in the case of ground source heat pumps it shall not exceed 3 months."

Priorities for action for climate-neutral heat up to 200 °C	Table 5
Overall framework: clear targets, efficient energy prices and a reform of network use charges	Stakeholder process to clarify goals (large-scale heat pump summit)
	Economic performance of electricity compared to gas; carbon pricing
	Network use charging that supports the energy system and faster connections to the network
Large-scale heat pumps: rapid cost reduction, further performance enhancements and greater production capacities	Standardisation, modularisation and scaling of products and processes
	Innovation focus: temperature lifts, efficiency increases and flexible operation; increased use of natural refrigerants
	Building up production capacity
District heating systems: a streamlined funding land-scape, mandatory planning and simplified implementation of large-scale heat pump projects	Increasing funding and removing perverse incentives
	Mandatory municipal heat planning and development into a municipal energy distribution strategy
	Accelerated planning, approval and implementation of large-scale heat pump projects

Agora Energiewende und Fraunhofer IEG (2023)

The recommendations for action made in this study represent a coherent and comprehensive package that can help the ambitious ramp-up of large-scale heat pumps and district heating systems to succeed. While further analyses and more precise information are needed in many areas, the study underlines the contribution that innovative approaches in heat supply can make to a successful transformation to climate neutrality – provided they are put into action quickly and ambitiously.

References

50Hertz Transmission GmbH; Amprion GmbH; TenneT TSO GmbH; TransnetBW GmbH (2022): *Modalitäten für Regelreserveanbieter.* Hg. v. 50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH und TransnetBW GmbH. Available online at https://www.regelleistung.net/ext/static/market-information, last update on 27.03.2023.

Acer (2023): *Report on Electricity Transmission and Distribution Tariff Methodologies in Europe.* Available online at https://www.acer.europa.eu/Publications/ACER_electricity_network_tariff_report.pdf.

AGO Energie (2023): *Industrie-, Groß- und Hochtemperaturwärmepumpen.* Available online at https://www.ago-energie.de/thermotechnik/ago-calora-industriewaermepumpe/, last checked on 05.04.2023.

Agora Energiewende, Prognos, Consentec (2022): *Klimaneutrales Stromsystem 2035. Wie der deutsche Stromsektor bis zum Jahr 2035 klimaneutral werden kann.* Available online at https://www.agora-energiewende.de/veroeffentlichungen/klimaneutraler-stromsektor-2035/.

Agora Energiewende (2022): *Volle Leistung aus der Energiekrise. Mit Zukunftsinvestitionen die fossile Inflation bekämpfen.* Available online at: https://www.agora-energiewende.de/veroeffentlichungen/volle-leistung-aus-der-energiekrise

Agora Energiewende (2023): *Die Energiewende in Deutschland: Stand der Dinge 2022. Rückblick auf die wesentlichen Entwicklungen sowie Ausblick auf 2023.* Available online at https://www.agora-energiewende.de/veroeffentlichungen/die-energiewende-in-deutschland-stand-der-dinge-2022/.

Agora Industry; FutureCamp (Hg.) (2022): *Power-2-Heat. Erdgaseinsparung und Klimaschutz in der Industrie.* Available online at https://www.agora-energiewende.de/veroeffentlichungen/power-2-heat-1/.

Arbeitsgemeinschaft Energiebilanzen e. V. (AGEB) (Hg.) (2022a): *Auswertungstabellen zur Energiebilanz Deutschland. Daten für die Jahre von 1990 bis 2021.* Available online at https://ag-energiebilanzen.de/daten-und-fakten/auswertungstabellen/.

Arbeitsgemeinschaft Energiebilanzen e. V. (AGEB) (2022b): *Anwendungsbilanzen zur Energiebilanz Deutschland. Endenergieverbrauch nach Energieträgern und Anwendungszwecken. Detaillierte Anwendungsbilanzen der Endenergiesektoren für 2020 und 2021.* Available online at https://ag-energiebilanzen.de/daten-und-fakten/anwendungsbilanzen/.

Arbeitsgruppe Erneuerbare Energien-Statistik (AGEE) (2022): *Zeitreihen zur Entwicklung der erneuerbaren Energien in Deutschland.* Available online at https://www.erneuerbare-energien.de/EE/Navigation/DE/Service/Erneuerbare_Energien_in_Zahlen/Zeitreihen/zeitreihen.html.

Arpagaus, Cordin (2019): *Hochtemperatur-Wärmepumpen. Marktübersicht, Stand der Technik und Anwendungspotenziale.* Berlin, Offenbach: VDE VERLAG GMBH.

Arpagaus, Cordin (2020): *Literaturstudie zum Stand der Technik, der Forschung, des Anwendungspotenzials und der Kältemittel.* Hg. v. NTB Interstaatliche Hochschule für Technik Buchs.

Bacquet, Alexandre; Galindo Fernández, Marina; Oger, Alexis; Themessl, Niko; Fallahnejad, Mostafa; Kranzl, Lukas; Popovski, Eftim; Steinbach, Jan; Burger, Veit; Köhler, Benjamin; Braungardt, Sibylle; Billerbeck, Anna; Breitschopf, Barbara; Winkler, Jenny (2022): *District heating and cooling in the European Union: overview of markets and regulatory frameworks under the revised Renewable Energy Directive.* Hg. v. European Commission, Directorate-General for Energy. Luxembourg.

BASF (2022): *BASF und MAN Energy Solutions vereinbaren Zusammenarbeit für den Bau einer der weltgrößten Wärmepumpen in Ludwigshafen.* Available online at https://www.basf.com/global/de/media/news-releases/2022/07/p-22-278.html, last checked on 05.04.2023.

Billerbeck, Anna; George, Jan Frederick; Müller, Paul Viktor; Winkler, Jenny; Timofeeva, Elena; Weidinger, Lisa; Greitzer, Maria; Hanßke, Anja; Nolden, Christoph; Jentsch, Andrej; Sercan-Çalişmaz, Kibriye (2023): *Analyse aktueller ökonomischer Rahmenbedingungen für Großwärmepumpen. Bericht Arbeitspaket 1.* Hg. v. Fraunhofer ISI, Fraunhofer IEG und Der Energieeffizienzverband für Wärme, Kälte und KWK e. V. (AGFW).

Boer, Robert de; Marina, Andrew; Zühlsdorf, Benjamin; Arpagaus, Cordin; Bantle, Michael; Wilk, Veronika; Elmegaard, Brian; Corberán, José; Benson, Jessica (2020): *Strengthening Industrial Heat Pump Innovation: Decarbonizing Industrial Heat.* Hg. v. Netherlands Organisation for Applied Scientific Research, Danish Technological Institute, NTB – Die Interstaatliche Hochschule für Technik, Austrian Institute of Technology (SINTEF), Research Institutes of Sweden (RISE) und Polytechnic University of Valencia.

Born, Holger; Bracke, Rolf; Eicker, Timm; Rath, Michael (2022): *Roadmap Oberflächennahe Geothermie. Erdwärmepumpen für die Energiewende – Potenziale, Hemmnisse und Handlungsempfehlungen.* Hg. v. Fraunhofer IEG.

Boston Consulting Group (BCG); Bundesverband der Deutschen Industrie e. V. (BDI) (2021): *Klimapfade 2.0. Ein Wirtschaftsprogramm für Klima und Zukunft.*

Bracke, Rolf; Bussmann, Gregor; Eicker, Timm; Ignacy, Roman; Jagert, Felix; Danowski-Buhren, Christian; Schmidt, Benno (2018): *Potenzialstudie Warmes Grubenwasser.* Hg. v. Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen (LANUV).

Bracke, Rolf; Ernst, Huenges; Acksel, Daniel; Amann, Florian; Bremer, Judith; Bruhn, David et al. (2022): *Roadmap tiefe Geothermie für Deutschland. Handlungsempfehlungen für Politik, Wirtschaft und Wissenschaft für eine erfolgreiche Wärmewende. Strategiepapier von sechs Einrichtungen der Fraunhofer-Gesellschaft und der Helmholtz-Gemeinschaft.* Hg. v. Fraunhofer IEG und Helmholtz-Zentrum Potsdam Deutsches GeoForschungsZentrum (GFZ). Fraunhofer IEG; Fraunhofer IBP; Fraunhofer UMSICHT.

Breitschopf, Barbara; Wohlfarth, Kathatrina; Schlomann, Barbara; Billerbeck, Anna; Preuß, Sabine; Bagheri, Mahsa; Berger, Frederic; Schmidt, Ralf-Roman; Stefanica, Dan; Muinzer, Thomas L. (2022): *Overview of heating and cooling. Perceptions, markets and regulatory frameworks for decarbonisation: final report.* Hg. v. European Commission. Available online at https://data.europa.eu/doi/10.2833/962558, last checked on 20.03.2023.

Brunner, Florian; Krummenacher, Pier (2017): *Einführung in die Prozessintegration mit der Pinch-Methode. Handbuch für die Analyse von kontinuierlichen Prozessen und Batch-Prozessen.* Zweite Auflage. Im Auftrag des Bundesamt für Energie, Sektion Industrie und Dienstleistungen. Schweiz.

Bundesamt für Wirtschaft und Ausfuhrkontrolle (BAFA) (Hg.) (2018): *Merkblatt für innovative KWK-Systeme zur Darlegung der Zulassungsvoraussetzungen nach dem Kraft-Wärme-Kopplungsgesetz (KWKG) i. V. m. der KWK-Ausschreibungsverordnung (KWKAusV).*

Bundesamt für Wirtschaft und Ausfuhrkontrolle (BAFA) (Hg.) (2022a): *Bundesförderung für effiziente Wärmenetze (BEW). Modul 3: Antragstellung und Verwendungsnachweis.* Available online at https://www.bafa.de/DE/Energie/Energieeffizienz/Waermenetze/Effiziente_Waermenetze/effiziente_waermenetze_node.html, last checked on 15.03.2023.

Bundesamt für Wirtschaft und Ausfuhrkontrolle (BAFA) (Hg.) (2022b): *Bundesförderung für effiziente Wärmenetze: technische Anforderungen der Module 1 bis 4.* Available online at https://www.bafa.de/DE/Energie/Energieeffizienz/Waermenetze/Effiziente_Waermenetze/effiziente_waermenetze_node.html, last checked on 12.12.2022.

Bundesministerium für Wirtschaft und Klimaschutz (BMWK) (Hg.) (2023): *Wohlstand klimaneutral erneuern. Werkstattbericht des Bundesministerium für Wirtschaft und Klimaschutz (BMWK).* Available online at https://www.bmwk.de/Redaktion/DE/Publikationen/Wirtschaft/werkstattbericht-des-bmwk.pdf?__blob=publicationFile&v=10, last checked on 30.03.2023.

Bundesnetzagentur (BNetzA) (Hg.) (2023a): *Marktstammdatenregister.* Available online at https://www.marktstammdatenregister.de/MaStR/, last update on 10.01.2023.

Bundesnetzagentur (BNetzA) (Hg.) (2023b): *Monitoringbericht 2022. Monitoringbericht gemäß § 63 Abs. 3 i.V.m. § 35 EnWG und § 48 Abs. 3 i.V.m. § 53 Abs. 3 GWB.* Available online at https://www.bundesnetzagentur.de/DE/Fachthemen/ElektrizitaetundGas/Monitoringberichte/start.html.

Bundesverband der Energie- und Wasserwirtschaft e. V. (BDEW) (Hg.) (2022): *Die Energieversorgung 2022. Jahresbericht.*

Bundesverband Erneuerbare Energien e. V. (BEE) (03.08.2022): *BEW kann starten. Wichtiger erster Schritt für grüne Wärmenetze.* Available online at https://www.presseportal.de/pm/51135/5288415, last checked on 13.10.2022.

Bundesverband Wärmepumpe e. V. (BWP) (2019): *Gewerbeobjekte und Industrieanlagen mit Wärmepump.* Available online at https://www.waermepumpe.de/waermepumpe/gewerbeobjekte-industrieanlagen/, last checked on 05.04.2023.

Bundesverband Wärmepumpe e. V. (BWP) (2020): *Gienger: ein Unternehmen mit Geschichte und Vision.* Available online at https://www.waermepumpe.de/presse/pressefahrten/rhein-neckar-kreis-2020/bibliothek-in-historischem-gebaeude-heizt-und-kuehlt-mit-geothermie0/#content, last checked on 05.04.2023.

Bundesverband Wärmepumpe e. V. (BWP) (2022a): *Energiekonzept für Münchens Werksviertel.* Available online at https://www.waermepumpe.de/presse/pressefahrten/raum-muenchen-2022/energiekonzept-fuer-muenchens-werksviertel/#content, last checked on 05.04.2023.

Bundesverband Wärmepumpe e. V. (BWP) (2022b): *Innovative Heiztechnik.* Available online at https://www.waermepumpe.de/presse/pressefahrten/raum-muenchen-2022/innovative-heiztechnik/#-content, last checked on 11.04.2023.

Bundesverband Wärmepumpe e. V. (BWP) (2022c): *Wärme- und Kältekonzepte mit Großwärmepumpen.* Available online at https://www.waermepumpe.de/waermepumpe/grosswaermepumpen/, last checked on 05.04.2023.

Bundesverband Wärmepumpe e. V. (BWP) (2023a): *AGO Calora Stadtwerke Neuburg.* Available online at https://www.waermepumpe.de/presse/referenz-objekte/bwp-datenbank, last checked on 05.04.2023.

Bundesverband Wärmepumpe e. V. (BWP) (2023b): *Referenzobjekte.* Available online at https://www.waermepumpe.de/presse/referenzobjekte/bwp-datenbank/, last checked on 06.04.2023.

Carrier (2023): *Klimatisierung & Heizung.* Available online at https://www.carrier.com/commercial/de/de/produkte/klimatisierung-und-heizung/, last checked on 05.04.2023.

Combitherm (2023): *Wärmepumpen.* Available online at https://www.combitherm.de/produkte-und-loesungen/waermepumpen/, last checked on 05.04.2023.

Danish Energy Agency (Hg.) (2022): *Energy Statistics 2021.* Available online at https://ens.dk/en/our-services/statistics-data-key-figures-and-energy-maps/annual-and-monthly-statistics.

Der Energieeffizienzverband für Wärme, Kälte und KWK e. V. (AGFW) (2020): *Leitfaden zur Erschließung von Abwärmequellen für die Fernwärmeversorgung. Frankfurt am Main.* Available online at https://www.agfw.de/fileadmin/AGFW_News_Mediadateien/Energiewende_Politik/agfwleitfaden_ansicht_es.pdf.

Der Energieeffizienzverband für Wärme, Kälte und KWK e. V. (AGFW) (2022): *AGFW Hauptbericht 2021.* Available online at https://www.agfw.de/zahlen-und-statistiken/agfw-hauptbericht.

Der Energieeffizienzverband für Wärme, Kälte und KWK e. V. (AGFW), Andrej Jentsch (2023a), 13.02.2023. *E-Mail to Fraunhofer IEG.*

Der Energieeffizienzverband für Wärme, Kälte und KWK e. V. (AGFW) (2023b): *Reallabor der Energiewende: Großwärmepumpen in Fernwärmenetzen.* Available online at https://www.agfw.de/reallabor-gwp/, last update on Januar 2023, last checked on 09.03.2023.

Der Energieeffizienzverband für Wärme, Kälte und KWK e. V. (AGFW) (2023c): *Bau eines iKWK-Systems in Lemgo.* Available online at https://www.gruene-fernwaerme.de/praxisbeispiele/lemgo, last checked on 11.04.2023.

Deutsche Energie-Agentur GmbH (dena) (2021): *dena-Leitstudie Aufbruch Klimaneutralität. Eine gesamtgeselschaftliche Aufgabe.* Available online at https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2021/Abschlussbericht_dena-Leitstudie_Aufbruch_Klimaneutralitaet.pdf.

Deutsche Energie-Agentur GmbH (dena) (2022): *Abschlussbericht: Erkenntnisse aus dem Stakeholderdialog industrielle Produktionskapazitäten für die Energiewende (StiPE). Entwurf einer industriepolitischen Strategie für Erneuerbare Energien und Stromnetze.* Unter Mitarbeit von Philine Wedell, Joscha Müller, Shervin Balali, Philipp Barthel, Mirko Bolsenbroek, Tibor Fischer et al.

Dierks, Stefanie (2022): *Ostsee soll Wärme für neues Quartier liefern.* Hg. v. energate messenger. Available online at https://www.energate-messenger.de/news/228893/ostsee-soll-waerme-fuer-neues-quartier-liefern, last checked on 06.04.2023.

Duisburger Versorgungs- und Verkehrsgesellschaft, Sabine Tiepelmann (2023), 23.02.2023. *E-Mail to Fraunhofer IEG.*

Ecke, Julius; Göke, Leonard (2017): *Energie aus Abwasser: Das bislang unbekannte Potential für die Wärmewende.* Hg. v. enervis energy advisors GmbH.

enercity (2022): *Enercity stellt Anlagen für Wärmewende vor und ruft Hannover zum Energiesparen auf.* Available online at https://www.enercity.de/presse/pressemitteilungen/2022/enercity-stellt-anlagen-fuer-waermewende-vor-und-ruft-hannover-zum-energiesparen-auf, last checked on 06.04.2023.

energie.de (2021): *Großwärmepumpen zur Dekarbonisierung der Wärmeversorgung.* Available online at https://www.energie.de/euroheatpower/news-detailansicht/nsctrl/detail/News/grosswaermepumpen-zur-dekarbonisierung-der-waermeversorgung/np/2, last checked on 05.04.2023.

energie-experten (2023a): *Dettenhauseneer Wärmenetz nutzt BHKW-Abwärme.* Available online at https://www.energie-experten.org/projekte/dettenhausener-waermenetz-waermepumpe-nutzt-bhkw-abwaerme, last checked on 05.04.2023.

energie-experten (2023b): *Spatenstich für iKWK in Stein.* Available online at https://www.energie-experten.org/projekte/spatenstich-fuer-ikwk-in-stein, last checked on 05.04.2023.

Energiewendebauen (2023): *Start Reallabor der Energiewende GWP.* Available online at https://www.energiewendebauen.de/projekt/neu-grosswaermepumpen-in-deutschen-fernwaermenetzen/, last checked on 05.04.2023.

enertime (2023): *Very High Temperature Heat Pump and Steam Generation Heat Pump.* Available online at https://www.enertime.com/en/solutions/heat-pumps, last checked on 05.04.2023.

Engie Refrigeration (2023): *ENGIE Refrigeration in Zahlen.* Available online at https://www.engie-refrigeration.de/de, last checked on 05.04.2023.

Euroheat & Power (2022): *Large Heat Pumps in District Heating and Cooling Systems.* Available online at https://www.euroheat.org/resource/report-large-heat-pumps-in-district-heating-and-cooling-systems.html.

Europäische Kommission (EK) (Hg.) (2022): *5548 final, 2.8.2022, State Aid SA.63177 (2022/N). Germany Federal support for efficient heat networks.* Available online at https://ec.europa.eu/competition/elojade/isef/case_details.cfm?proc_code=3_SA_63177.

European Commission (2023): *Communication: A Green Deal Industrial Plan for the Net-Zero Age.* Available online at https://commission.europa.eu/document/41514677-9598-4d89-a572-abe21cb037f4_en. European Chemicals Agency (ECHA) (2023): Annex XV RESTRICTION REPORT. PROPOSAL FOR A RESTRICTION. Available online at www.echa.europa.eu/.

European Chemicals Agency (ECHA) (2023): *Annex XV RESTRICTION REPORT. PROPOSAL FOR A RESTRICTION.* Available online at www.echa.europa.eu/.

Fédération des opérateurs d'efficacité énergétique et de chaleur renouvelable (FEDENE); Syndicat National du Chauffage Urbain et de la Climatisation Urbaine (SNCU) (Hg.) (2022): *Enquête des Réseaux de Chaleur et de Froid. Édition 2022.* Available online at https://reseaux-chaleur.cerema.fr/espace-documentaire/enquete-nationale-annuelle-des-reseaux-chaleur-et-froid.

Fenagy (2023): *Heat Pumps.* Available online at https://www.fenagy.dk/en/products-heat-pumps, last checked on 05.04.2023.

Fischer, Dennis (2022): *Energiepark Tiefstack soll Hamburger Kohleausstieg vollenden.* Hg. v. energate messenger. Available online at https://www.energate-messenger.de/news/223279/energiepark-tiefstack-soll-hamburger-kohleausstieg-vollenden, last checked on 06.04.2023.

Fraunhofer ISI; Consentec; ifeu; TU Berlin E&R (2021): *Langfristszenarien für die Transformation des Energiesystems in Deutschland 3. TN-Szenarien.* Available online at https://www.langfristszenarien.de/.

Fraunhofer ISI; Consentec; ifeu; TU Berlin E&R (2022a): *Langfristszenarien für die Transformation des Energiesystems in Deutschland.* Webinar zum Energieangebot / Umwandlungssektor.

Fraunhofer ISI; Consentec; ifeu; TU Berlin E&R (2022b): *Langfristszenarien für die Transformation des Energiesystems in Deutschland 3. T45-Szenarien.* Available online at https://www.langfristszenarien.de/.

Friotherm (2023): *Produkte: Unitop® – dauerhaft und effizient.* Available online at https://www.friotherm.de/produkte/unitop/, last checked on 05.04.2023.

Fritz, Sara; Pehnt, Martin (2018): *Kommunale Abwässer als Potenzial für die Wärmewende?* Institut für Energie- und Umweltforschung (IFEU). Available online at https://www.ifeu.de/publikation/kommunale-abwaesser-als-potenzial-fuer-die-waermewende/.

Gaudard, Adrien; Schmid, Martin; Wüest, Alfred (2018): *Thermische Nutzung von Seen und Flüssen. Potenzial der Schweizer Oberflächengewässer.* In: Aqua & Gas N°2.

GEA (2023): *Wärmepumpen.* Available online at https://www.gea.com/de/products/refrigeration-heating/heat-pumps/index.jsp?i=refrigeration-heating, last checked on 05.04.2023.

Gerhardt, Norman; Ganal, Irina; Jentsch, Mareike; Rodriguez, Juan; Stroh, Kilian; Buchmann, Elisabeth Klara (2019): *Entwicklung der Gebäudewärme und Rückkopplung mit dem Energiesystem in -95 Prozent THG Klimazielszenarien.* Fraunhofer IEE.

Gerhardt, Norman; Zimmermann, Britta; Ganal, Irina; Pape, Angela; Gíron, Pedro; Ghosh, Debraj; Dörre, Elias; Kallert, Anna; Yu, Young-Jae (2021): *Transformationspfade im Wärmesektor – Betriebs- und volkswirtschaftliche Betrachtung der Sektorkopplung mit dem Fokus Fernwärme mit hohen Anteilen konventioneller KWK-Erzeugung und Rückkopplung zum Gesamtenergieversorgungssystem.* Available online at https://www.iee.fraunhofer.de/de/projekte/suche/laufende/transformationspfade-im-waermesektor.html, last checked on 01.08.2022.

Government Offices of Sweden (2023): *Sweden's carbon tax. Government Offices of Sweden.* Available online at https://government.se/government-policy/swedens-carbon-tax/swedens-carbon-tax/, last update on 2023, last checked on 24.03.2023.

Grosse, Robert; BinderChristopher; Wöll, Stefan; Geyer, Roman; Steffen, Robbi (2017): *Long term (2050) projections of techno-economic performance of large-scale heating and cooling in the EU. EUR 28859 EN.* Publications Office of the European Union. Luxembourg.

Heaten (2023): *The HeatBooster.* Available online at https://www.heaten.com/product/, last checked on 05.04.2023.

Hochmuth, Sebastian (2022): *Großwärmepumpen Rosenheim.* Hg. v. Stadtwerke Rosenheim (SW.aktiv).

Holdinghausen, Heike (2022): *Wärmewende aus der Tiefe. Der Clou von Schwerin.* Available online at https://taz.de/Waermewende-aus-der-Tiefe/!5883053/, last checked on 06.04.2023.

Hybrid Energy (2023): *Products.* Available online at https://www.hybridenergy.no/products/, last checked on 05.04.2023.

International Energy Agency (IEA) (Hg.) (2018-2024): *Annex TS4. Digitalisation of District Heating and Cooling.* Available online at https://www.iea-dhc.org/the-research/annexes/2018-2024-annex-ts4, last checked on 06.04.2023.

International Energy Agency (IEA) (2021-2025a): *Annex TS6. Status Assessment, Ageing, Lifetime Prediction and Asset Management of District Heating Pipes.* Available online at https://www.iea-dhc.org/the-research/2021-2025-annex-ts6, last checked on 06.04.2023.

International Energy Agency (IEA) (2021-2025b): *Annex TS7. Industry-DHC Symbiosis.* Available online at https://www.iea-dhc.org/2021-2025-annex-ts7, last checked on 06.04.2023.

International Energy Agency (IEA) (2022a): *Annex 58. High-Temperature Heat Pumps. Cascade Heat Pump System for District Heating.* Available online at https://heatpumpingtechnologies.org/annex58/wp-content/uploads/sites/70/2022/07/johnsonhthpannex58.pdf.

International Energy Agency (IEA) (2022b): *High-Temperature Heat Pumps – IEA HPT TCP ANNEX58.* Unter Mitarbeit von Benjamin Zühlsdorf und Jonas Lundsted Poulsen. Available online at www.heatpumpingtechnologies.org/annex58.

International Energy Agency (IEA) (2023a): *Annex 58. High-Temperature Heat Pumps.* Available online at https://heatpumpingtechnologies.org/annex58/wp-content/uploads/sites/70/2022/07/mvr-hp-epcon-evaporation-technology.pdf, last checked on 06.04.2023.

International Energy Agency (IEA) (2023b): *Annex 58. Task 1: Technologies – State of the art and ongoing developments for systems and components.* Available online at https://heatpumpingtechnologies.org/annex58/task1/, last checked on 13.04.2023.

International Energy Agency (IEA) (2023c): *Annex 59. Heatpumps for drying.* Available online at https://heatpumpingtechnologies.org/annex59/, last checked on 06.04.2023.

Jakobs; Stadtländer (2020): *Industrial Heat Pumps, Second Phase.* Hg. v. International Energy Agency (IEA). Available online at https://waermepumpe-izw.de/wp-content/uploads/2021/04/IEA-HPT-TCP-Annex-48.pdf, last checked on 05.04.2023.

Jakobs, Rainer (2017): *Annex 35 + 48. Heat Pump Applikation in Commercial and Industrial Processes.* Hg. v. International Energy Agency (IEA). Available online at https://waermepumpe-izw.de/wp-content/uploads/2020/05/2017_09_-WS_HTHP_IEA-HPT-A48_Jakobs.pdf, last checked on 05.04.2023.

Johnson Controls (2023). *Wärmepumpenlösungen.* Available online at https://www.johnsoncontrols.com/de_de/hvac/waerme-pumpen-loesungen, last checked on 05.04.2023.

K21 media GmbH (Hg.) (2023): *Kooperation zur Abwärmenutzung.* Available online at https://www.stadt-und-werk.de/meldung_40399_Kooperation+zur+Abw%C3%A4rmenutzung.html, last checked on 06.04.2023.

Kammer, Henriette (2018): *Thermische Seewassernutzung in Deutschland. Bestandsanalyse, Potential und Hemmnisse seewasserbetriebener Wärmepumpen.* Wiesbaden: Springer Fachmeien Wiesbaden.

Klimaschutz- und Energieagentur Baden-Württemberg GmbH (KEA-BW) (2022): *Technikkatalog zur kommunalen Wärmeplanung in Baden-Württemberg.* Available online at https://www.kea-bw.de/waermewende/wissensportal/technikkatalog, last checked on 31.03.2023.

KKT Chillers (2023): *Hochleistungswärmepumpe – Magma.* Available online at https://www.kkt-chillers.com/prozesskuehlung/thermodynamixx/magma.html, last checked on 05.04.2023.

Kreiskrankenhaus Freiberg (2023): *Silberbergwerk als energetische Goldgrube.* Available online at https://www.kkh-freiberg.com/ueber-uns/gute-gruende-fuer-uns/energetische-optimierung/, last checked on 06.04.2023.

Mateu-Royo, Carlos; Arpagaus, Cordin; Mota-Babiloni, Adrián; Navarro-Esbrí, Joaquín; Bertsch, Stefan S. (2021): *Advanced high temperature heat pump configurations using low GWP refrigerants for industrial waste heat recovery: A comprehensive study.* In: Energy Conversion and Management 229, S. 113752. DOI: 10.1016/j.enconman.2020.113752.

Mayekawa (2023): *Produkte.* Available online at http://www.mayekawa.eu/de/produkte, last checked on 05.04.2023.

Mellwig, Peter (2022): *Langfristszenarien für die Transformation des Energiesystems in Deutschland. Energienachfrage Gebäudesektor.* Folien zum Webinar. Institut für Energie- und Umweltforschung (IFEU). Available online at https://www.langfristszenarien.de/enertile-explorer-de/dokumente/.

Mellwig, Peter; Lempik, Julia; Blömer, Sebastian; Pehnt, Martin (2021): *Langfristszenarien 3. Modul Gebäude.* Available online at https://www.langfristszenarien.de/enertile-explorer-wAssets/docs/LFS-Gebaeude.pdf.

Menzel, Nora (2022): *Großwärmepumpe bei Evonik in Herne erzeugt Fernwärme fürs Ruhrgebiet.* Hg. v. Chemie Technik. Available online at https://www.chemietechnik.de/energie-utilities/grosswaerme-pumpe-bei-evonik-in-herne-erzeugt-fernwaerme-fuers-ruhrgebiet-841.html, last checked on 05.04.2023.

Mercator Research Institute on Global Commons and Climate Change (MCC) (2023): *CO_2-Bepreisung zur Erreichung der Klimaneutralität im Verkehrs- und Gebäudesektor: Investitionsanreize und Verteilungswirkungen.* Unter Mitarbeit von Matthias Kalkuhl, Maximilian Kellner, Tobias Bergmann und Karolina Rütten.

Mitsubishi (2023): *Water to Water. Centrifugal Heat Pump.* Available online at http://mitsubishivrf.net/katalog/mitsubishi-heavy-industries-etw-su-dan-suya-isi-pompasi.pdf, last checked on 05.04.2023.

MVV Umwelt GmbH (2023): *R(h)ein mit der Wärme. MVV installiert eine der größten Flußwärmepumpen Europas.* Available online at https://www.mvv.de/ueber-uns/unternehmensgruppe/mvv-umwelt/aktuelle-projekte/mvv-flusswaermepumpe?category=0&question=1996, last checked on 06.04.2023.

Nekså, Petter; Bantle, Michael; Schlemminger, Christian; Bamigbetan, Opeyemi (2019): *High temperature industrial heat pumps utilising natural working fluids.* Proceedings of the 25th IIR International Congress of Refrigeration, Montréal, Canada, August 24-30, 2019. Available online at http://dx.doi.org/10.18462/iir.icr.2019.1253

Norsk Fjernvarme (2023): *Energikilder.* Available online at https://www.fjernvarme.no/fakta/energikilder, last checked on 16.03.2023.

Ochsner (2023a): *Höchsttemperatur-Baureihen (IWWDS, ISWDS, IWWDSS).* Available online at https://ochsner-energietechnik.com/hoechsttemperatur-waermepumpen/, last checked on 05.04.2023.

Ochsner (2023b): *Ochsner Energietechnik Referenzprojekte.* Available online at https://ochsner-energietechnik.com/referenzen/, last checked on 05.04.2023.

Oilon (2023); *Industrielle Wärmepumpen und Wasserkühler. ChillHeat.* Available online at https://oilon.com/wp-content/uploads/2020/11/Oilon-ChillHeat-DE.pdf, last checked on 05.04.2023.

Olvondo (2023): *The Technology. What is a high temperature heat pump and how does it work?* Available online at https://www.olvondotech.no/the-technology/, last checked on 05.04.2023.

Pachai, Alexander; Normann, Jeannett; Arpagaus, Cordin; Hafner, Armin (2021): *Screening of Future-Proof Working Fluids for Industrial High-Temperature Heat Pumps up to 250 °.* In: 9th IIR Conference: Ammonia and CO_2 Refrigeration Technologies.

Pieper, Henrik; Ommen, Torben; Buhler, Fabian; Paaske, Bjarke Lava; Elmegaard, Brian; Markussen, Wiebke Brix (2018): *Allocation of investment costs for large-scale heat pumps supplying district heating.* In: Energy Procedia 147, S. 358–367. DOI: 10.1016/j.egypro.2018.07.104.

Potsdam-Institut für Klimafolgenforschung (PIK) (2021): *Deutschland auf dem Weg zur Klimaneutralität 2045. Szenarien und Pfade im Modellvergleich (Kopernikus-Projekt Ariadne).* Available online at https://doi.org/10.48485/pik.2021.006.

Potsdam-Institut für Klimafolgenforschung (PIK) (2022): *Kopernikus-Projekt Ariadne. Szenarienvergleich der „Big 5" Klimaneutralitätsszenarien.* Unter Mitarbeit von Luderer, Kost und Sörgel. Available online at https://ariadneprojekt.de/news/big5-szenarienvergleich/.

Prognos; Öko-Institut; Wuppertal-Institut (2021): *Klimaneutrales Deutschland 2045. Wie Deutschland seine Klimaziele schon vor 2050 erreichen kann.* Hg. v. Stiftung Klimaneutralität, Agora Energiewende, Agora Verkehrswende. Available online at https://www.agora-energiewende.de/veroeffentlichungen/klimaneutrales-deutschland-2045-vollversion/.

Sachverständigenrat für Verbraucherfragen (SVRV) (2022): *Eine faire CO_2-Bepreisung macht es Verbraucher*innen leicht, sich klimafreundlich zu entscheiden.* Unter Mitarbeit von Christian Gross, Veronika Grimm und Gert G. Wagner.

Seipp, Allegra; Grüning, Christine; Moslener, Ulf (2016): *Absicherung von Fündigkeitsrisiken bei Geothermieprojekten.* Report Nr. 01/2016. Hg. v. Frankfurt School – UNEP Collaborating Centre for Climate & Sustainable Energy Finance.

Siemens Energy (2021): *Vattenfall und Siemens Energy treiben mit Großwärmepumpe die klimafreundliche Wärmeversorgung Berlin voran.* Available online at https://press.siemens-energy.com/global/de/pressemitteilung/vattenfall-und-siemens-energy-treiben-mit-grosswaermepumpe-die-klimafreundliche, last checked on 05.04.2023.

Siemens Energy (2023a): *Heat Pumps. Proven high and low temperature heat pumps for up to 150°C and 70 MWth.* Available online at https://www.siemens-energy.com/global/en/offerings/power-generation/heat-pumps.html, last checked on 05.04.2023.

Siemens Energy (2023a): *Large-scale Industrial Heat Pumps.* Available online at https://www.siemens-energy.com/global/en/offerings/power-generation/heat-pumps.html.

Soroka, Bohdan (2015): *Application Note – Industrial Heat Pumps.* Hg. v. European Copper Institute.

SRM (2023): *SRMTEC Group.* Available online at https://www.srmtec.group/index-2.html, last checked on 05.04.2023.

Stadt Heidelberg (2022): *Flusswärmepumpe wird künftig Baustein für klimaneutrale Wärmeversorgung sein, last update on* https://www.heidelberg.de/hd/HD/service/24_05_2022+flusswaerme-pumpe+wird+kuenftig+baustein+fuer+klimaneu-trale+waermeversorgung+sein.html, last checked on 06.04.2023.

Stadtwerke Cottbus, Patrik Hillwig (2023), 27.03.2023. *E-Mail to Fraunhofer IEG.*

Stadtwerke Heidelberg, Tobias Enders (2023), 27.02.2023. *E-Mail to Fraunhofer IEG.*

Stadtwerke Kiel (2023): *Dekarbonisierung der Kieler Fernwärme.* Available online at https://www.stadtwerke-kiel.de/privatkunden/angebote-tarife/waerme/waermewende-kiel/dekarbonisi-erung-der-kieler-fernwaerme, last checked on 06.04.2023.

Stadtwerke Münster (2023): *Erster Baustein für grüne Wärme entsteht im Hafen.* Available online at https://www.stadtwerke-muenster.de/presse/pressemeldungen/gesamt/nachricht/artikel/erster-baustein-fuer-gruene-waerme-entsteht-im-hafen.html.

Stadtwerke Schwerin (2022): *Geothermie in Schwerin: Wärmepumpen wurden geliefert.* Available online at https://www.pressebox.de/pressemitteilung/stadtwerke-schwerin-gmbh/geothermie-in-schwerin-waermepump-en-wurden-geliefert/boxid/1126438, last checked on 06.04.2023.

Stadtwerke Stuttgart (2023): *Klimaneutral: Quartier am Neckarpark.* Available online at https://www.stadtwerke-stuttgart.de/partner-der-energiewende/neckarpark/, last checked on 17.01.2023.

Star Refrigeration (2023): *Water Source Neatpump.* Available online at https://www.star-ref.co.uk/products/heat-pumps/water-source-heat-pump-neatpump/, last checked on 05.04.2023.

Stathopoulos, Panos (2022): *Wärmepumpen als eine Option zur Elektrifizierung und Dekarbonisi-erung des Industriellen Wärmebedarfs – Die neuartigen DLR-Hochtemperatur-Wärmepumpen.* DLR, 2022.

Statistisches Amt der Europäischen Kommission (Eurostat) (2023a): *Elektrizitätspreiskomponenten für Nichthaushaltskunde, ab 2007 – jährliche Daten.* Available online at https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_205_c/default/table, last update on 02.02.2023, last checked on 22.02.2023.

Statistisches Amt der Europäischen Kommission (Eurostat) (2023b): *Gaspreiskomponenten für Nich-thaushaltskunden – jährliche Daten.* Available online at https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_203_c/default/table, last update on 02.02.2023, last checked on 22.02.2023.

Statistisches Amt der Europäischen Kommission (Eurostat) (2023c): *Preise Elektrizität für Nich-thaushaltskunde, ab 2007 – halbjährliche Daten.* Available online at https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_205/default/table, last update on 24.01.2023, last checked on 20.02.2023.

Statistisches Amt der Europäischen Kommission (Eurostat) (2023d): *Preise Gas für Nichthaushalt-skunde, ab 2007 – halbjährliche Daten.* Available online at https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_203/default/table, last update on 01.02.2023, last checked on 20.02.2023.

Statistiska centralbyrån (SCB) (2022): *District heating (GWh).* Available online at https://www.scb.se/en/finding-statistics/statistics-by-subject-area/energy/energy-supply-and-use/annual-ener-gy-statistics-electricity-gas-and-district-heating/

pong/tables-and-graphs/district-heating-gwh/, last update on 27.10.2022, last checked on 16.03.2023.

Stobbe, Lutz; Proske, Marina; Zedel, Hannes; Hintemann, Ralph; Clausen, Jens; Beucker, Severin (2015): *Entwicklung des IKT-bedingten Strombedarfs in Deutschland.* Fraunhofer IZM; Borderstep Institut.

Swegon (2023): *Luft Luft Wärmepumpe & Co.: Wärmepumpen und Kaltwassererzeuger zum Heizen und Kühlen.* Available online at https://www.swegon.com/de/produkte/kuhlen--heizen/, last checked on 05.04.2023.

Teuffer, Mareike (2022): *Hamburg plant 60 MW-Abwasser-Wärmepumpe.* Hg. v. energate messenger. Available online at https://www.energate-messenger.de/news/226723/hamburg-plant-60-mw-abwasser-waermepumpe, last checked on 05.04.2023.

The World Bank (Hg.) (2022): *Carbon Pricing Dashboard.* Available online at https://carbonpricingdashboard.worldbank.org/map_data, last update on 01.04.2022.

Tix, Michaela (2022a): *Ibbenbüren: Luftwärmepumpe halbiert den Primärenergiefaktor.* Available online at https://www.energate-messenger.de/news/220415/ibbenbueren-luftwaermepumpe-halbiert-den-primaerenergiefaktor, last checked on 05.04.2023.

Tix, Michaela (2022b): *Stadtwerke Gotha prüfen zwei Optionen zur Großwärmepumpe.* Available online at https://www.energate-messenger.de/news/226563/stadtwerke-gotha-pruefen-zwei-optionen-zur-grosswaermepumpe, last checked on 06.04.2023.

Tix, Michaela (2022c): *Stadtwerke Münster bauen Groß-Wärmepumpe am Kanal. Hg. v. energate messenger.* Available online at https://www.energate-messenger.de/news/225036/stadtwerke-muenster-bauen-gross-waermepumpe-am-kanal, last checked on 05.04.2023.

Tix, Michaela (2023): *Bad Salzuflen plant drei Wärmepumpen am Klärwerk. Hg. v. energate messenger.* Available online at https://www.energate-messenger.de/news/229573/bad-salzuflen-plant-drei-waermepumpen-am-klaerwerk, last checked on 05.04.2023.

Turboden (2023): *Large Heat Pump.* Available online at https://www.turboden.com/solutions/2602/large-heat-pump, last checked on 05.04.2023.

Umweltbundesamt (UBA) (2017): *Prognos AG, Fraunhofer ISI, TU München im Auftrag des Umweltbundesamtes: Datenbasis zur Bewertung von Energieeffizienzmaßnahmen in der Zeitreihe 2005–2014.* Available online at https://www.umwelt-bundesamt.de/sites/default/files/medien/1968/publikationen/2017-01-09_cc_01-2017_endbericht-datenbasis-energieeffizienz.pdf

Umweltbundesamt (UBA) (2022): *Entwicklung der spezifischen Kohlendioxid – Emissionen des deutschen Strommix in den Jahren 1990–2020.* Available online at https://www.umweltbundesamt.de/publikationen/entwicklung-der-spezifischen-kohlendioxid-8.

Umweltbundesamt (UBA) (Hg.) (2023a): *Dekarbonisierung von Energieinfrastrukturen. Ein politischer Unterstützungsrahmen für das Beispiel Wärmenetze.* Unter Mitarbeit von Sara Ortner, Martin Pehnt, Margarete Over, Sebastian Blömer, Susanne Ochse, Ziegler, Roland, Bohm, Kerstin et al. Available online at https://www.umweltbundesamt.de/publikationen/dekarbonisierung-von-energieinfrastrukturen.

Umweltbundesamt (UBA) (Hg.) (2023b): *Öffentliche Abwasserentsorgung.* Available online at https://www.umweltbundesamt.de/daten/wasser/wasserwirtschaft/oeffentliche-abwasserentsorgung#rund-10-milliarden-kubikmeter-abwasser-jahrlich, last checked on 05.04.2023.

Umweltbundesamt (UBA) (Hg.) (2023c): *Berechnung der Treibhausgasemissionsdaten für das Jahr 2022 gemäß Bundesklimaschutzgesetz. Begleitender Bericht.* Available online at https://www.umweltbundesamt.de/sites/default/files/medien/361/dokumente/vjs_2022_-_begleitbericht_final_kurzfassung.pdf.

umweltwirtschaft.com (2023): *Berlin steckt voller Energie. Erstes Flusswasser-Kraftwerk in Berlin.* Available online at https://www.umweltwirtschaft.com/news/energie/Berlin-steckt-voller-Energie-Erstes-Flusswasser-Kraftwerk-in-Berlin--28131.

Vattenfall (2022): *Neue Wärmepumpe für das Stadtwärmenetz in Berlin Buch.* Available online at https://group.vattenfall.com/de/newsroom/news/2022/neue-waermepumpe-stadtwaerme-berlin, last checked on 05.04.2023.

Viessmann (2023a): *Wärmepumpe.* Available online at https://www.viessmann.de/de/wissen/technik-und-systeme/waermepumpe.html, last checked on 05.04.2023.

Viessmann (2023b): *Referenzen.* Available online at https://www.viessmann.de/de/referenzen.html, last checked on 06.01.2023.

VDI-Richtlinie 2067 Blatt 1 (2012): *Wirtschaftlichkeit gebäudetechnischer Anlagen.*

Wolf, Stefan (2017): *Integration von Wärmepumpen in industrielle Produktionssysteme. Potenziale und Instrumente zur Potenzialerschließung.* Universität Stuttgart. Institut für Energiewirtschaft und Rationelle Energieanwendung (IER).

Zeitung für kommunale Wirtschaft (Hg.) (2022): *Stadtwerke Flensburg bauen Großwärmepumpe bis 2025.* Available online at https://www.zfk.de/energie/waerme/stadtwerke-flensburg-bauen-gwp-bis-2025-klimaneutralitaet-grosswaermepumpe, last checked on 06.04.2023.

A.1 Overview of large-scale heat pump projects and detailed description of selected projects

Overview of large-scale heat pump projects in district heating systems — Table 6

Heat source	Status	Thermal output	Temperature of heat source	Flow temperature	COP	Sources
Waste heat	operational	0.5 MW	–	–	–	BWP (2022c)
Waste heat (industrial)	planned	≥ 0.5 MW	–	up to 130 °C	–	Menzel (2022)
Waste heat (cooling unit)	operational	8.0 MW	32 °C	85–120 °C	ca. 3.0	Siemens Energy (2021)
Waste heat (cooling unit)	operational	1.2 MW	–	–	–	BWP (2022a)
Waste heat (power plant)	under construction	2.0 MW	–	120 °C	–	Stadtwerke Münster (2023)
Waste heat (power plant)	under construction	20.5 MW	7.5–28 °C winter: 7.5–20 °C	90 °C	2.8	Energiewendebauen (2023); AGFW (2023a)
Waste heat (power plant)	under construction	1.2 MW	38–48 °C	80 °C	5.4	AGFW (2023a); Energiewendebauen (2023)
Waste heat (power plant)	operational	≥ 0.5 MW	–	–	–	energie-experten (2023a)
Waste heat (power plant)	operational	0.7 MW	40 °C	65 °C	6.4	Vattenfall (2022)
Wastewater, sewage plants	planned	0.5 MW	–	–	–	Tix (2023)
Wastewater, sewage plants	planned	4.0 MW	10–25 °C	75–85 °C	2.5–3.3	Duisburger Versorgungs- und Verkehrsgesellschaft (2023)
Wastewater, sewage plants	planned	60 MW	ca. 14 °C	85 °C	ca. 3	Teuffer (2022)
Wastewater, sewage plants	operational	2.4 MW	13 °C (average temperature)	90 °C	2.7	energie.de (2021)
Wastewater, sewage plants	operational	3.0 kW	–	–	–	Stadtwerke Stuttgart (2023)
Ambient air	planned	0.8 MW	–	–	–	Tix (2022a)
Ambient air	under construction	1.4 MW	operating above 13 °C	85 °C	2.8	Stadtwerke Heidelberg (2023)
Ambient air	under construction	0.9 MW	–	–	–	energie-experten (2023b)
Ambient air	operational	1.4 MW	–	–	–	BWP (2022c)

Heat source	Status	Thermal output	Temperature of heat source	Flow temperature	COP	Sources
River water	planned	230 MW	–	–	–	Fischer (2022)
River water	planned	≥ 0.5 MW	–	–	–	Stadt Heidelberg (2022)
River water	planned	2.0 MW	–	–	–	Tix (2022c)
River water	under construction	20.5 MW	3–25 °C winter: 3–12 °C	83–99 °C	2.5–3.0	MVV Umwelt GmbH (2023)
River water	under construction	4.7 MW	3–21 °C winter: 3–12 °C	88 °C	2.5–2.8	Hochmuth (2022)
River water	under construction	7.0 MW	operating above 8 °C	95 °C	ca. 2.5	umweltwirtschaft.com (2023)
River water	operational	1.0 MW	–	–	–	AGFW (2023c)
Pit water	planned	3.0 MW	18 °C	48 °C	–	Fraunhofer IEG
Pit water	under construction	0.5 MW	60 °C	80–120 °C	–	IEA (2022a)
Groundwater	operational	2.0 MW	–	–	4	BWP (2023b)
Sea water	planned	≥ 0.5 MW	–	60–85 °C	–	Zeitung für kommunale Wirtschaft (2022)
Sea water	planned	0.7 MW	min. 4 °C	–	–	Dierks (2022)
Sea water	planned	50–80 MW	2–25 °C	80–115 °C	–	Stadtwerke Kiel (2023)
Near-surface geothermal energy	operational	0.8 MW	–	–	–	BWP (2023b)
Lake water	planned	35 MW	4–15 °C	95–125 °C	> 2.5	Stadtwerke Cottbus (2023)
Servers and data centres	planned	20.0 MW	–	–	–	K21 media GmbH (2023)
Deep geothermal energy	planned	7.4 MW	56 °C	75–80 °C	–	Holdinghausen (2022); Stadtwerke Schwerin (2022)
Groundwater and waste heat (cooling unit)	operational	1.2 MW	40 °C	60 °C	3.6	BWP (2023b)
Ambient air or near-surface geothermal energy	planned	1.2 MW	–	–	–	Tix (2022b)
Multiple heat sources	planned	1.2 MW				Energiewendebauen (2023)
No information	under construction	≥ 0.5 MW	–	–	–	enercity (2022)

Fraunhofer IEG based on sources cited (see last column)

Overview of large-scale heat pump projects in decentralised heat supply and industrial processes — Table 7

Heat source	Status	Thermal output	Temperature of heat source	Flow temperature	COP	Sources
Waste heat	operational	3.5 MW	–	58 °C	–	Jakobs (2017)
Waste heat	operational	1.7 MW	26–29 °C	75 °C	5.6	Jakobs und Stadtländer (2020)
Waste heat	operational	0.8 MW	–	90 °C	–	Jakobs und Stadtländer (2020)
Waste heat (industrial)	planned	120 MW	–	–	–	BASF (2022)
Waste heat (industrial)	operational	3.3 MW	23 °C	35 °C	6.3	Jakobs und Stadtländer (2020)
Waste heat (power plant)	operational	10 MW	39 °C	78 °C	4.5	Jakobs und Stadtländer (2020)
Waste heat (district heating)	operational	1.0 MW	–	–	4.5	BWP (2023a)
Waste water and sewage treatment plants	operational	1.5 MW	10 °C	40 °C	–	Ochsner (2023b)
Ambient air	operational	1.4 MW	–	–	–	BWP (2020)
Pit water	operational	0.9 MW	14 °C	up to 70 °C	–	Kreiskrankenhaus Freiberg (2023)
Groundwater	operational	1.3 MW	–	–	–	BWP (2023b)
Groundwater	operational	4.9 MW	–	–	–	BWP (2019)
Groundwater	operational	4.5 MW	10 °C	50 °C	4.7–5.8	BWP (2019)
Groundwater	operational	0.9 MW	10–12 °C	–	–	BWP (2022b)
Groundwater	operational	1.6 MW	10 °C	55 °C	5.6	Viessmann (2023b)
Near-surface geothermal energy	operational	1.7 MW	–	–	4.2	BWP (2023b)
Near-surface geothermal energy	operational	1.0 MW	–	–	–	BWP (2023b)
Near-surface geothermal energy	operational	1.4 MW	–	–	3	BWP (2023b)

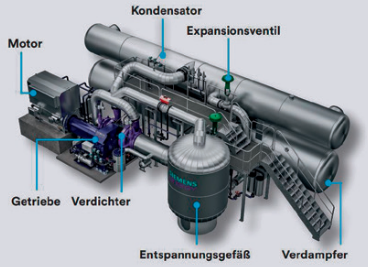
Fraunhofer IEG based on sources cited (see last column)

Information sheet Duisburg			
Waste water heat pump Duisburg			
Operator	Stadtwerke Duisburg AG		
Other project partners	Wirtschaftsbetriebe Duisburg AöR		
Location	Duisburg-Huckingen (DE)		
Project type	Waste water heat pump for district heating		
Launch	Planned for 1st quarter 2025		
Heat source	Waste water (pure water treatment plant), volume flow strongly fluctuating		
	Temperature of heat source: 10–25 °C		
Heat sink	District heating (flow temperature of heating network: 75–130 °C)		
	Flow temperature of heat pump: 75–85 °C		
COP	2.5–3.3		
Technical data			
Heat pump manufacturer	Not yet known		
Model	Not yet known		
Thermal output	Heat: 2 x 2 MW		
Electrical output	Not yet known (ammonia, natural refrigerant)		
Compressor	Not yet known		
Refrigerant	R717 (ammonia, natural refrigerant)		
Dimensions	Not yet known	Weight	Not yet known
Sound pressure level	Not yet known		
Hours in operation	4 000 hours per year planned		
Additional systems	Gas engine (2 x 4.5 MW), electric boiler (30 MW) at other site		
Heat storage	no		
CO_2 avoidance, investment volume and funding			
CO_2 avoidance	Not yet known		
Investment volume	Not yet known		
Funding	iKWK award, June 2021		

Duisburger Versorgung- und Verkehrsgesellschaft; Tiepelmann, Sabine (2021): iKWK-Stadtwerke Pitch. Duisburger Versorgungs- und Verkehrsgesellschaft. Available online at https://www.youtube.com/watch?v=0HtHmZuSakQ, accessed 24/01/2023. Duisburger Versorgungs- und Verkehrsgesellschaft (2023); correspondence between S. Tiepelmann and Fraunhofer IEG energie.de (2021): Stadtwerke Duisburg errichten größte iKWK-Anlage Deutschlands an einer Kläranlage. Available online at https:// www.energie.de/eurohe-atpower/news-detailansicht/nsctrl/detail/News/stadtwerke-duisburg-errichten-groesste-ikwk-anlage-deutschlands-an-einer-klaeranlage, accessed 24/01/2023.

Information sheet on the Mannheim river water heat pump

Reallabor – Mannheim



Operator	MVV AG	
Other project partners	IER Universität Stuttgart, Fraunhofer ISE, AGFW	
Location	Mannheim (DE)	
Project type	River water heat pump for district heating network	
Launch	Planned for 2023	
Heat source	River water	
	Temperature of heat source: 3–25 °C; during heating season 3–12 °C	
Heat sink	District heating (flow temperature of heating network: 83–129.9 °C)	
	Flow temperature of heat pump: 83–99 °C	
COP	2.5–3.0 (planned annual COP 2.7)	
Technical data		
Heat pump manufacturer	Siemens Energy	
Model	SHP 600	
Thermal output	Heat: 20.5 MW	
Electrical output	7 MW (load range: 65–100 percent)	
Compressor	Radial compressor	
Refrigerant	R1234ze(E) (HFO, synthetic refrigerant), ~12 000kg	
Dimensions	18 x 8.8 x 5.3 m	Weight: 142 t
Sound pressure level	(1 m) 97 dB(A)	
Hours in operation	2 000 h per year	
Additional systems	4 hard coal-fired cogeneration units (total 1 500 MW)	
Heat storage	43 000 m^3, 1 500 MWh	
CO_2 avoidance, investment volume and funding		
CO_2 avoidance	10 000 t per year	
Investment volume	800 €/kW, total 15 Mio. €	
Funding	BMWK Reallabor	

MVV Umwelt GmbH (2023): Grüne Wärme aus dem Rhein. Von der Idee zur Planung der MVV-Flusswärmepumpe, im Rahmen der AG-FW-Veranstaltung SW.aktiv am 04/10/2022. MVV: R(h)ein mit der Wärme. MVV installiert eine der größten Flusswärmepumpen Europa. Online available https://www.mvv.de/ueber-uns/unternehmensgruppe/mvv-umwelt/aktuelle-projekte/mvv-flusswaermepumpe?category=0&question=1996, accessed 24/01/2023. AGFW (2022): Correspondence between Dr. A. Jentsch (AGFW) and Fraunhofer IEG

Information sheet on the Rosenheim river water heat pump		
Reallabor–Rosenheim		
Operator	Stadtwerke Rosenheim	
Other project partners	IER Universität Stuttgart, Fraunhofer ISE, AGFW	
Location	Rosenheim (DE)	
Project type	Stream water heat pump for district heating network	
Launch	Planned for 2022/2023	
Heat source	River water, screened and sieved	
	Temperature of heat source: 3–21 °C; during heating season: 3–12 °C	
Heat sink	District heating	
	Flow temperature heat pump: 88 °C, then temperature increase to 90–120 °C through steam heat exchanger from waste incineration plant	
COP	2.5–2.8	
Technical data		
Heat pump manufacturer	Johnson Controls	
Model	SaBROE/NS-DualPAC	
Thermal output	Heating: 3 x 1 566 kW; cooling: 3 x 1 105 kW	
Electrical output	3 x 628 kW (load range: 40–100 percent)	
Compressor	Double-stage unit consisting of screw and piston compressor	
Refrigerant	R717 (ammonia, natural refrigerant), ca. 3 x 260 kg	
Dimensions	6.7 x 4.0 x 2.6 m per heat pump	Weight: 19 t per heat pump
Sound pressure level	108.9 dB(A)	
Hours in operation	4 000 h per year	
Additional systems	iKWK: Gas engine (4.5 MW), electric boiler (1.8 MW)	
Heat storage	1 000 m^3	
CO_2 avoidance, investment volume and funding		
CO_2 avoidance	Not yet known	
Investment volume	3.8 Mio. € (heat pumps), 8.5 Mio. € (incl. buildings and connections)	
Funding	iKWK award, BMWK-Reallabor	

Stadtwerke Rosenheim; Hochmuth, Sebastian (2022): Großwärmepumpen Rosenheim. Bau- und Betriebserfahrungen drei baugleicher Großwärmepumpen im Rahmen von iKWK-Systemen, im Rahmen der AGFW-Veranstaltung SW.aktiv am 04/10/2022. ENERGIEWENDE-BAUEN (2022): Neu: Großwärmepumpen in deutschen Fernwärmenetzen. Available online at https://www.energiewendebauen.de/projekt/neu-grosswaermepumpen-in-deutschen-fernwaermenetzen/, accessed 24/01/2023. AGFW (2022); correspondence between Dr A. Jentsch (AGFW) and Fraunhofer IEG

Information sheet on deep geothermal energy with heat pump Schwerin

Deep geothermal energy – Schwerin		
Operator	Stadtwerke Schwerin	
Other project partners	No information	
Location	Schwerin (DE)	
Project type	Deep geothermal energy with heat pump	
Launch	Not yet known	
Heat source	Deep geothermal (1 235 m)	
	Temperature of heat source: ca. 54 °C	
Heat sink	District heating flow temperature: 80/130 °C	
	Flow temperature of heat pump: 75–80 °C	
COP	Not yet known	
Technical data		
Heat pump manufacturer	Carrier	
Model	Type 61XWHHZE15 and 61XWHHZE10, total 4 WP	
Thermal output	7.35 MW	
Electrical output	Not yet known (load range: Not yet known)	
Compressor	Not yet known	
Refrigerant	R134a (HFKW, synthetic refrigerant), R1234ze (HFO, synthetic refrigerant)	
Dimensions	Not yet known	Weight: 9.5 and 7.3 t
Sound pressure level	Not yet known	
Hours in operation	Not yet known	
Additional systems	Not yet known	
Heat storage	Not yet known	
CO_2 avoidance, investment volume and funding		
CO_2 avoidance	Not yet known	
Investment volume	Entire plant 20 million €	
Funding	Funding from EFRE and KfW	

Stadtwerke Schwerin (2023) Geothermie. Available online at: https://www.stadtwerke-schwerin.de/home/ueber_uns/geothermie/ accessed (30/03/2023). Stadtwerke Schwerin (2022) Geothermie in Schwerin: Wärmepumpen wurden geliefert. Available online at: https://www.pressebox.de/ pressemitteilung/stadtwerke-schwerin-gmbh/Geothermie-in-Schwerin-Waermepumpen-wurden-geliefert/boxid/1126438. Accessed (01/02/2023). Holdinghausen, Heike (2022) Der Clou von Schwerin. Available online at: https://taz.de/Waermewende-aus-der-Tiefe/!5883053/. Accessed (01/02/2023). Carrier. AquaForce. Available online at: https://www.carrier.com/commercial/de/de/produkte/heizung/wasser-wasserwaermepumpen/61xwhze/. Accessed (01/02/2023). Carrier. 61 XW. Available online at: https://www.carrier.com/commercial/en/cn/products/commercial-products/chillers/61xw/. Accessed (01/02/2023). Stadtwerke Schwerin GmbH (2023); correspondence between Rüdiger, René (Stadtwerke Schwerin GmbH) and Fraunhofer IEG

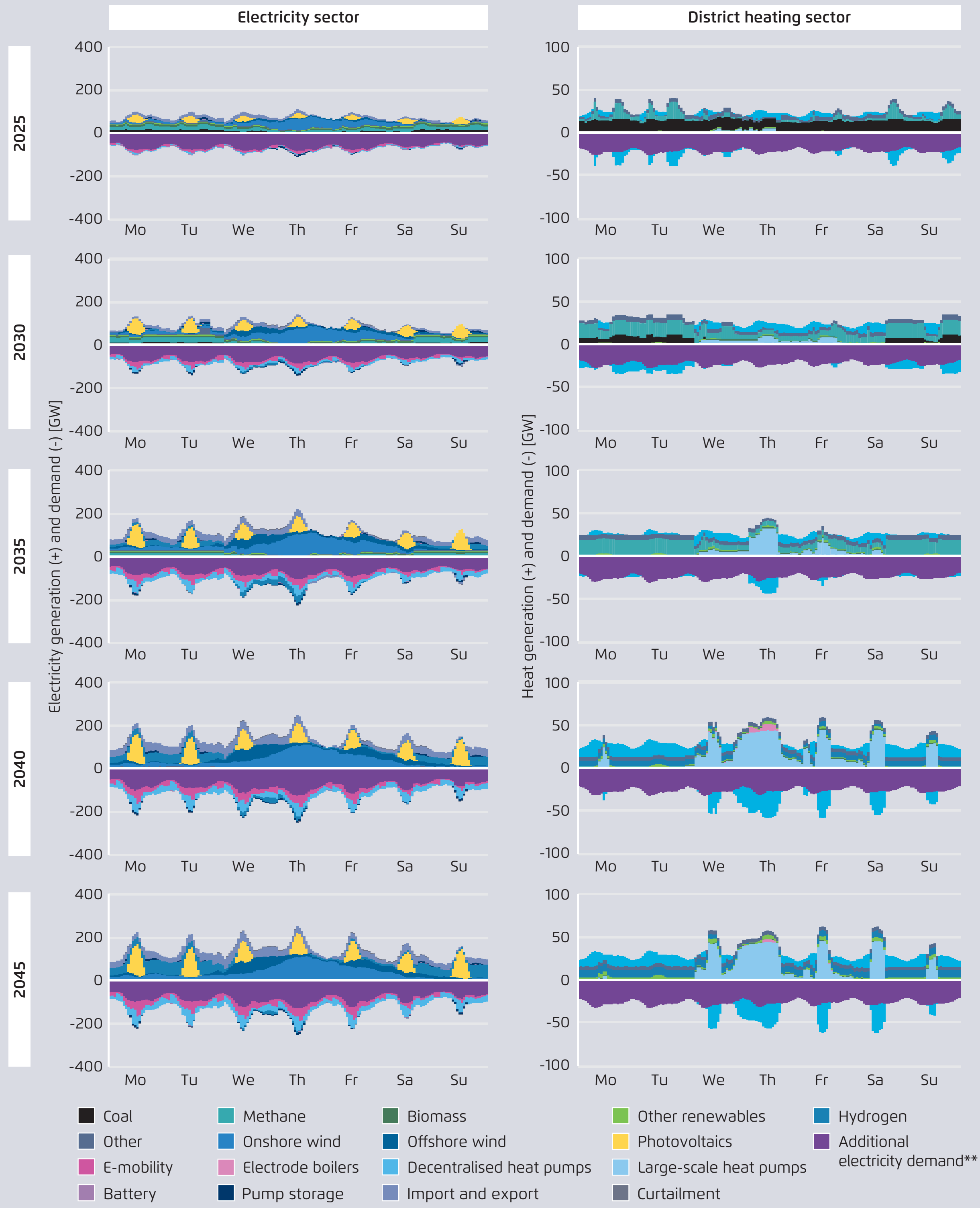
Information sheet on waste heat heat pump Stuttgart		
Reallabor – Stuttgart		
Operator	EnBW AG	
Other project partners	IER Universität Stuttgart, Fraunhofer ISE, AGFW, Mitsubishi	
Location	Stuttgart (DE)	
Project type	Waste heat from residual waste incineration for district heating	
Launch	Planned for 2023	
Heat source	Cooling water discharge to the Neckar from the residual waste heating power plant, river water filtered	
	Temperature of heat source: 7.5–28 °C; during heating season: 7.5–20 °C	
Heat sink	District heating flow temperature: 93 °C (medium temperature)	
	Flow temperature of heat pump: 90 °C	
COP	2.8	
Technical data		
Heat pump manufacturer	Johnson Controls	
Model	Not yet known	
Thermal output	Heat: 20.5 MW	
Electrical output	7 300 kW (load range: Not yet known)	
Compressor	Not yet known	
Refrigerant	R1234ze (HFO, synthetic refrigerant), 20 000 kg	
Dimensions	Not yet known	Weight: not yet known
Sound pressure level	Not yet known	
Hours in operation	ca. 3 000 h per year	
Additional systems	Currently: 3 waste boilers, 3 coal boilers	
Heat storage	No information	
CO_2 avoidance, investment volume and funding		
CO_2 avoidance	ca. 15 000 t CO_2 per year	
Investment volume	700–800 €/kW	
Funding	Reallabor (BMWK)	

Sources: Plattform Erneuerbare Energien Baden-Württemberg (2021): Webseminar: Großwärmepumpen–der nächste Schritt zur Wärmewende (Video). Available online at https://www.youtube.com/watch?v=Q37ORjeAuDQ, last checked on 24/01/2023. ENERGIEWENDEBAUEN (2022): Neu: Großwärmepumpen in deutschen Fernwärmenetzen. Available online at https://www.energiewendebauen.de/projekt/neu-grosswaermepumpen-in-deutschen-fernwaermenetzen/, last checked on 24/01/2023. AGFW (2022); correspondence between Dr A. Jentsch (AGFW) and Fraunhofer IEG

A.2 Dispatch and demand in the electricity and district heating sectors for all base years of the T45 scenarios „Electricity“ and „H_2“

Operation of the electricity and district heating sectors in a winter week* in the T45-Electricity scenario

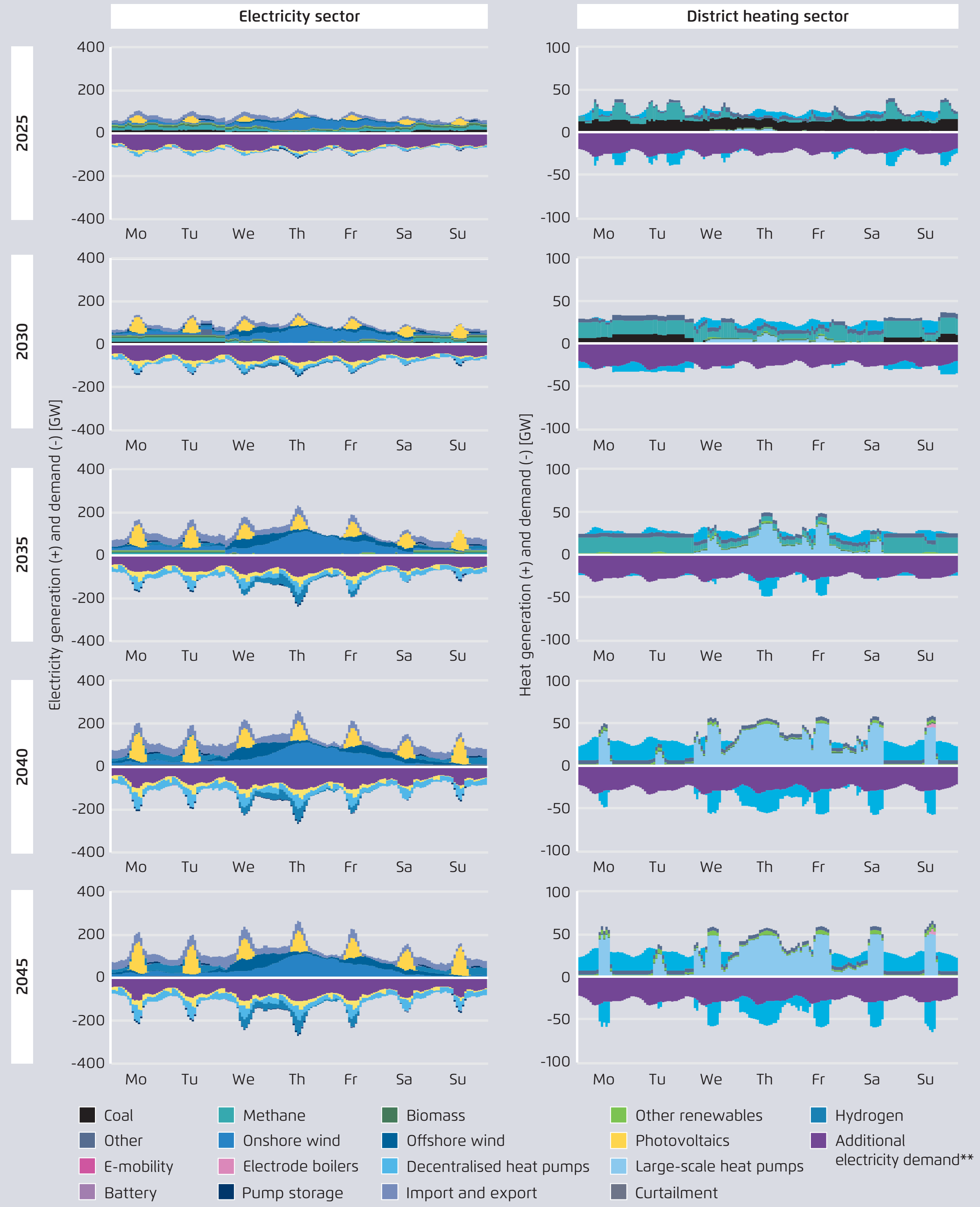
Figure 36



Fraunhofer IEG based on Fraunhofer ISI et al. (2022b). * Early February ** incl. electricity demand from large-scale heat pumps

Operation of the electricity and district heating sectors in a winter week* in the T45-H_2 scenario

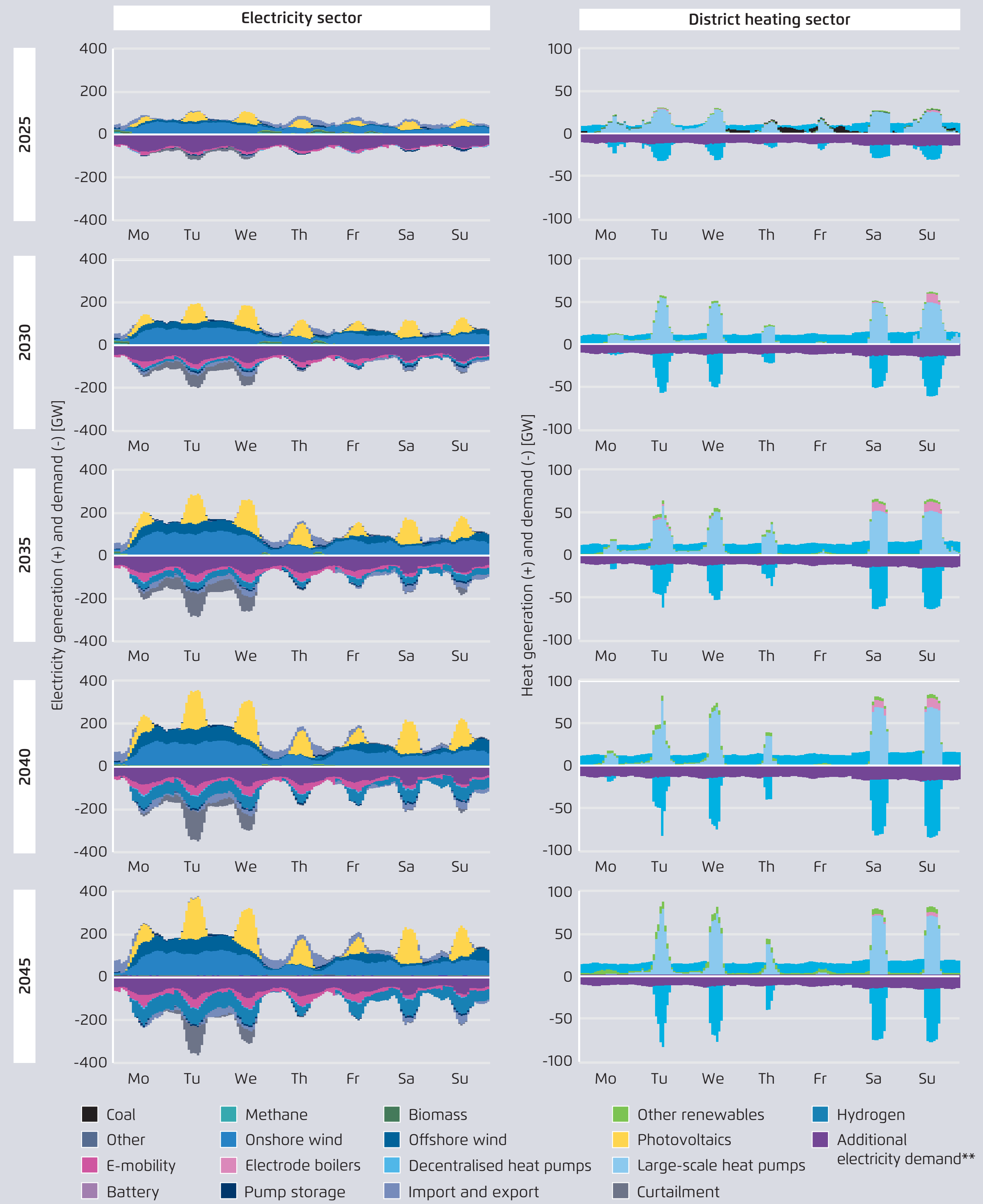
Figure 37



Fraunhofer IEG basierend auf Fraunhofer ISI et al. (2022b). * Early February ** incl. electricity demand from large-scale heat pumps

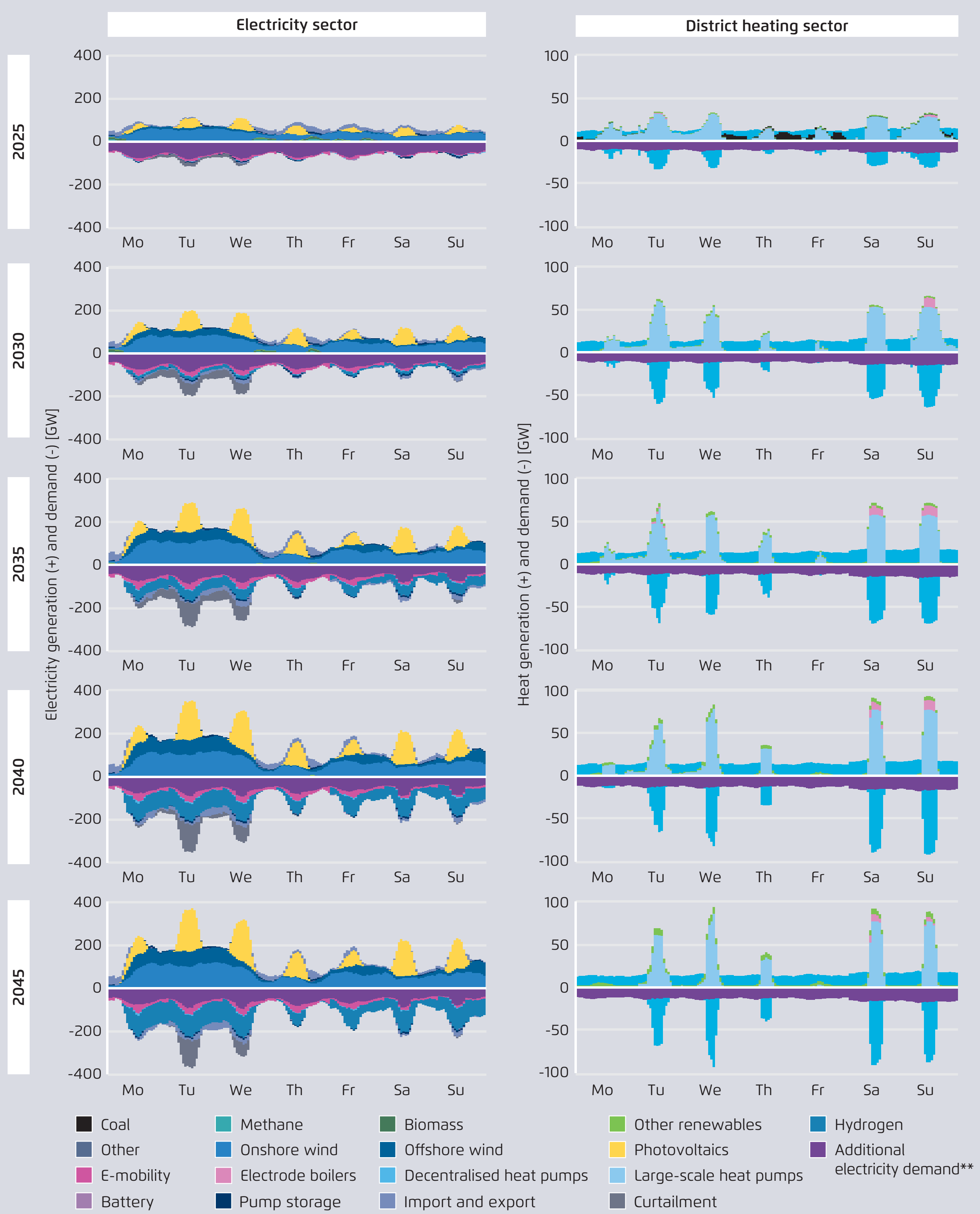
Operation of the electricity and district heating sectors in a summer week* in the T45-Electricity scenario

Figure 38



Fraunhofer IEG basierend auf Fraunhofer ISI et al. (2022b). * end of August. ** incl. electricity demand from large-scale heat pumps

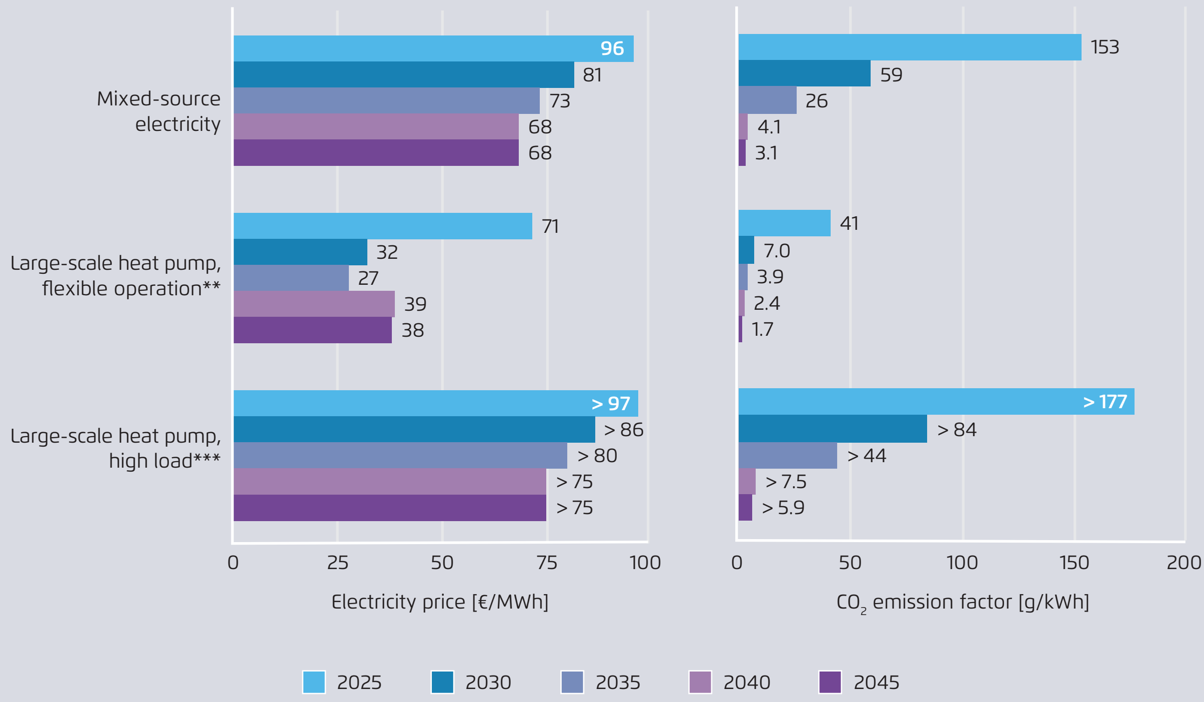
Operation of the electricity and district heating sectors in a summer week* in the T45-H_2 scenario — Figure 39



Fraunhofer IEG basierend auf Fraunhofer ISI et al. (2022b). * end of August. ** incl. electricity demand from large-scale heat pumps

Minimum economic and ecological benefits* of a flexible operation of large-scale heat pumps in the T45-Electricity scenario

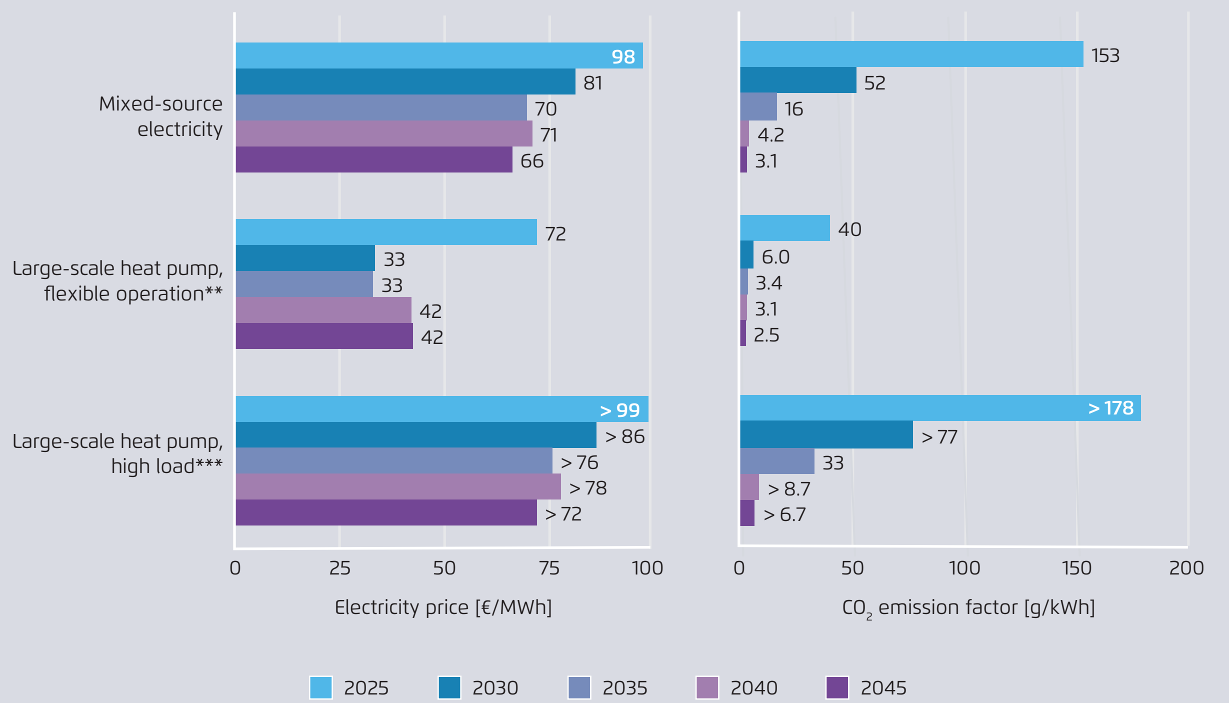
Figure 40



Fraunhofer IEG based on Fraunhofer ISI et al. (2022b) assuming a constant COP of 3.0. * Corresponds to economically optimised operation with low full load hours. ** Heat generation from the large-scale heat pump matches immediate heat demand (no use of heat storage). The maximum heat generation of the large-scale heat pump is limited so that 6 000 full load hours occur over the year. Assuming that the hourly wholesale prices and CO_2 emission factors on the electricity market do not change as a result of the change in the operating mode of the large-scale heat pump. *** Electricity price and CO_2 emission factor for operation under high load apply only to the first marginal unit. With each additional unit that switches from flexible operation to high-load operation, the price of electricity (and the CO_2 emission factor) increases, because increasingly expensive (and CO_2-intensive) electricity generation plants are needed to meet the additional demand.

Minimum economic and ecological benefits* of flexible operation of large-scale heat pumps in the T45-H_2 scenario

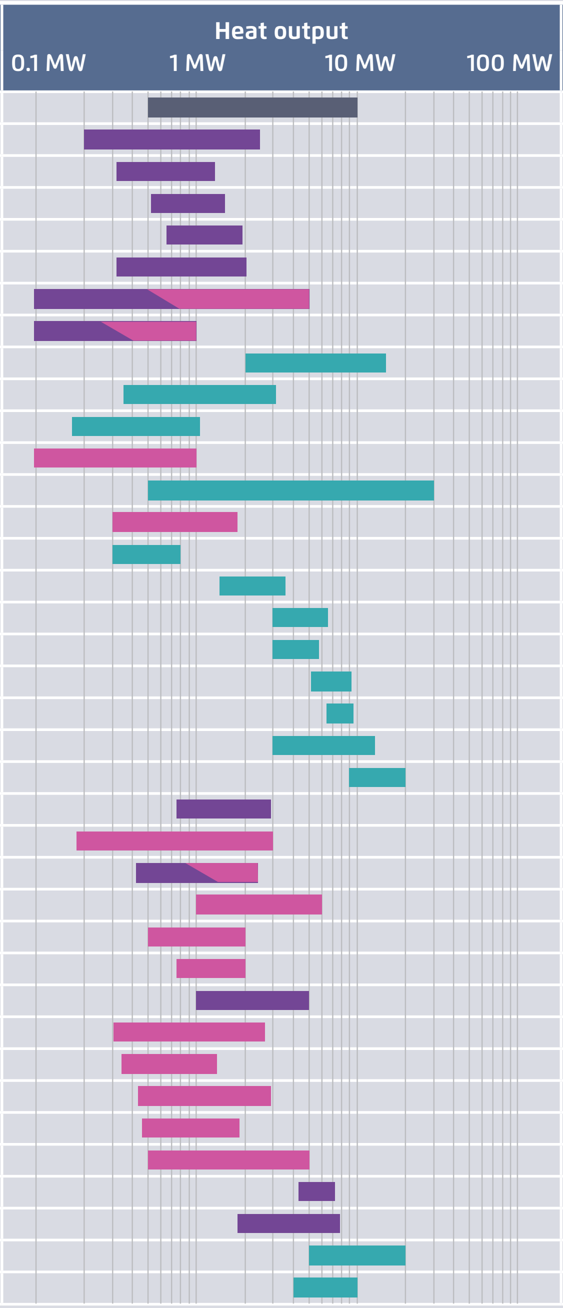
Figure 41



Fraunhofer IEG based on Fraunhofer ISI et al. (2022b) assuming a constant COP of 3.0. * Corresponds to economically optimised operation with low full load hours. ** Heat generation from the large-scale heat pump matches immediate heat demand (no use of heat storage). The maximum heat generation of the large-scale heat pump is limited so that 6 000 full load hours occur over the year. Assuming that the hourly wholesale prices and CO_2 emission factors on the electricity market do not change as a result of the change in the operating mode of the large-scale heat pump. *** Electricity price and CO_2 emission factor for operation under high load apply only to the first marginal unit. With each additional unit that switches from flexible operation to high-load operation, the price of electricity (and the CO_2 emission factor) increases, because increasingly expensive (and CO_2-intensive) electricity generation plants are needed to meet the additional demand.

A.3 Large-scale heat pump products on the market (TRL = 9) and other heat pump products and technologies

Overview of large-scale heat pumps available on the market (TRL = 9) Figure 42



Manufacturer	Max. flow temperature	Refrigerant
AGO Energie[1]	150 °C	R718/R717
Carrier[2]	85 °C	R1234ze
Carrier[2]	70 °C	R1234ze/R515B
Carrier[2]	55 °C	R1234ze/R515B
Carrier[2]	50 °C	R134a
Carrier[2]	63 °C	R134a
Combitherm[3]	80 °C	various
Combitherm[3]	120 °C	various
Enertime[4]	130 °C	R1233zdE
Engie Refrigeration[5]	65 °C	R1234ze/R515B
Engie Refrigeration[5]	50 °C	various
Engie Refrigeration[5]	90 °C	R744
EPCON (MVR)[6]	150 °C	R718
Fenagy[7]	120 °C	R744
Friotherm[8]	80 °C	R134a
Friotherm[8]	80 °C	R134a
Friotherm[8]	80 °C	R134a
Friotherm[8]	80 °C	R134a
Friotherm[8]	80 °C	R134a
Friotherm[8]	90 °C	R134a
Friotherm[8]	80 °C	R134a
Friotherm[8]	90 °C	R134a
GEA[9]	80 °C	R717
GEA[9]	95 °C	R717
GEA[9]	80 °C	R717
Heaten[10]	200 °C	HFOs
Hybrid Energy[11]	100 °C	R717/R718
Hybrid Energy[11]	120 °C	R717/R718
Hybrid Energy[11]	120 °C	R717/R718
Johnson Controls[12]	70 °C	R717
Johnson Controls[12]	90 °C	R717
Johnson Controls[12]	70 °C	R717
Johnson Controls[12]	90 °C	R717
Johnson Controls[12]	120 °C	R717 + R600
Johnson Controls[12]	95 °C	R717
Johnson Controls[12]	70 °C	R717
Johnson Controls[12]	93 °C	R1234ze
Johnson Controls[12]	93 °C	R1234ze

Screw compressor Piston compressor Turbo compressor Scroll compressor Other technology

Overview of large-scale heat pumps available on the market (TRL = 9) Figure 42

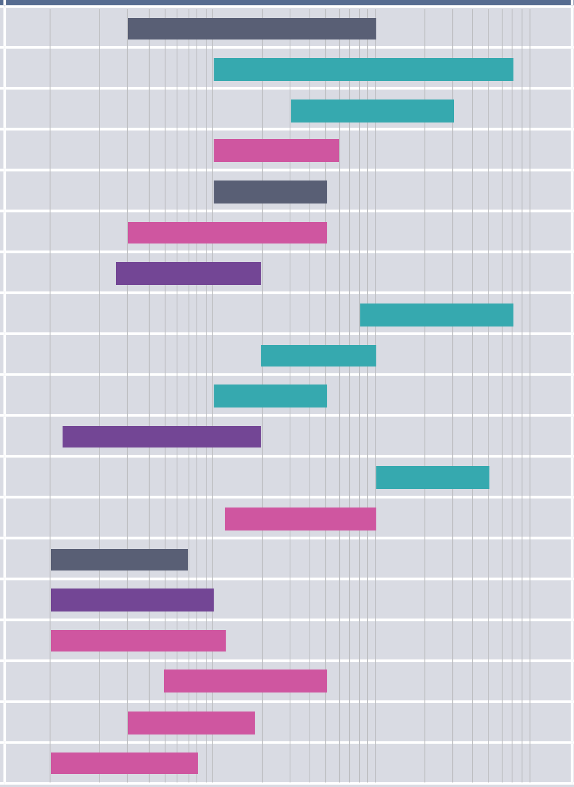
Manufacturer	Max. flow temperature	Refrigerant
Johnson Controls[12]	90 °C	R717
Johnson Controls[12]	90 °C	R134a
Johnson Controls[12]	50 °C	R134a, R513a
Johnson Controls[12]	93 °C	R1234ze
Johnson Controls[12]	50 °C	R1234ze
Johnson Controls[12]	68 °C	R1234ze
Johnson Controls[12]	50 °C	R1234ze
Johnson Controls[12]	63 °C	R513a
Johnson Controls[12]	65 °C	R134a
Johnson Controls[12]	50 °C	R410a
Johnson Controls[12]	55 °C	R410a
KKT Chillers[13]	70 °C	various
Kobelco[14]	165 °C	R245fa
Kobelco[14]	120 °C	R245fa
Mayekawa[15]	85 °C	R717
Mayekawa[15]	85 °C	R717
Mayekawa[15]	85 °C	R717
Mitsubishi[16]	90 °C	R134a
Ochsner[17]	130 °C	R245fa
Ochsner[17]	96 °C	R245fa
Ochsner[17]	75 °C	R134a
Oilon[18]	120 °C	various
Oilon[18]	85 °C	various
Oilon[18]	62 °C	R410A
Olvondo[19]	200 °C	R704
Siemens Energy[20]	100 °C	R1234ze u.a.
Siemens Energy[20]	150 °C	R1234ze u.a.
Spilling (MVR)[21]	250 °C	R718
SRM[22]	85 °C	R134a, R22, R717
Star Refrigeration[23]	130 °C	R717
Swegon[24]	63 °C	R513a, R134a
Swegon[24]	65 °C	R1234ze
Swegon[24]	65 °C	R1234ze
Swegon[24]	60 °C	R32
Turboden[25]	200 °C	various
Viessmann[26]	73 °C	R513a
Piller (MVR)[27]	212 °C	R718

Screw compressor | Piston compressor | Turbo compressor | Scroll compressor | Other technology

Fraunhofer IEG based on (1) AGO Energie (2023), (2) Carrier (2023), (3) Combitherm (2023), (4) enertime (2023), (5) Engie Refrigeration (2023), (6) IEA (2023b), (7) Fenagy (2023), (8) Friotherm (2023), (9) GEA (2023), (10) Heaten (2023), (11) Hybrid Energy (2023), (12) Johnson Controls (2023), (13) KKT Chillers (2023), (14) IEA (2023b), (15) Mayekawa (2023), (16) Mitsubishi (2023), (17) Ochsner (2023a), (18) Oilon (2023), (19) Olvondo (2023), (20) Siemens Energy (2023a), (21) IEA (2023b), (22) SRM (2023), (23) Star Refrigeration (2023), (24) Swegon (2023), (25) Turboden (2023), (26) Viessmann (2023a), (27) IEA (2023b)

Overview of new or improved large-scale heat pumps (TRL < 9) according to IEA HPT Annex 58 Figure 43

Manufacturer	Max. flow temperature	Heat output (0.1 MW · 1 MW · 10 MW · 100 MW)	Refrigerant	TRL
Enerin	250 °C		R704	6
Piller (MVR)	212 °C		R718	8–9
Turboden	200 °C		various	7–9
Heaten	200 °C		HFOs	7–9
ToCircle	188 °C		R717/R718	6–7
spHeat	165 °C		HFOs	6–8
SRM	165 °C		R718	5
Simens Energy	160 °C		various	7–8
Enertime	160 °C		HFOs	4–8
Weel & Sandvig	160 °C		R718	4–9
Rank	160 °C		various	7
MAN	150 °C		R744	7–8
Ohmia Industy	150 °C		R717/R718	7–8
ecop	150 °C		Noble gas	6–7
Mayekawa	145 °C		R601	5
GEA	130 °C		R744	8
Johnson Controls	120 °C		R717 + R600	7–8
Fenagy	120 °C		R744	5–6
Mayekawa	120 °C		R600	7



Screw compressor · Piston compressor · Turbo compressor · Scroll compressor · Other technology

Fraunhofer IEG based on IEA (2023b)

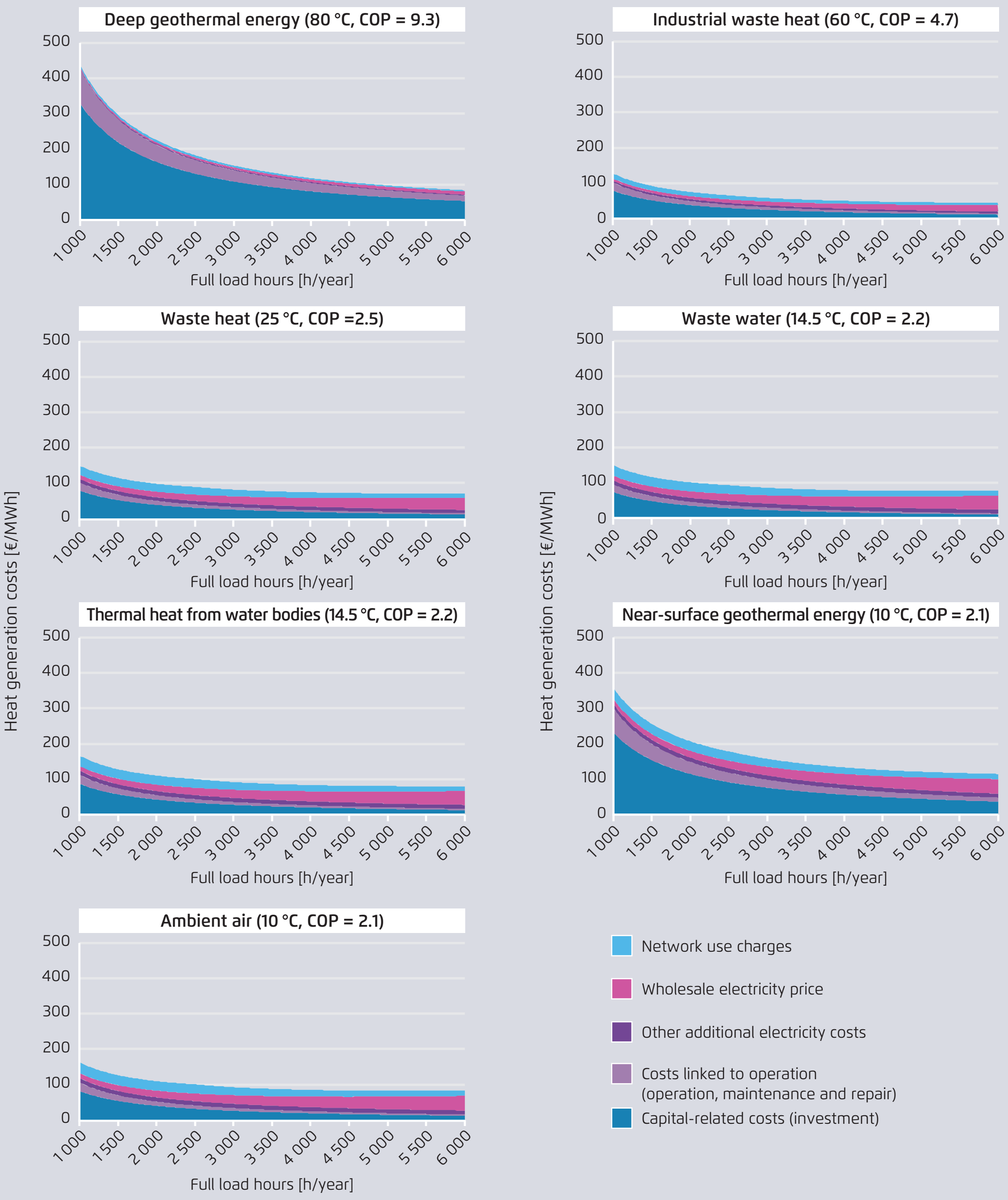
Overview of other market-ready and novel heat pump technologies — Table 8

Technology	Mode of operation	Applications	Pros and cons
Absorption and adsorption heat pump TRL = 9	Temperature increase through absorption and desorption of a refrigerant with thermal drive power	Space heating, hot water, district heating and process heat up to 150 °C	+ No mechanical drive required + COP less dependent on source temperature – Usually fossil fuel for drive heat – Usually less efficent as a rule
Mechanical vapour recom-pression (MVR) TRL = 9	Open compression heat pump using process steam as refrigerant	Generation and processing of process steam up to 280 °C in energy-intensive process industries	+ Very high sink temperatures possible + High COP – High source temperature needed – Applications limited due to open operating mode
Thermal vapour recompression TRL = 9	Open compression by means of a steam jet compressor, driven by hot process steam	Heat supply for distilla-tion, cooking, evapora-tion and stripping processes to increase efficiency in process engineering in the food, paper and chemical industries	+ Cost-effective – Restricted temperature and applications ranges
Rotation heat pump (ecop) TRL = 6–7	Rotating heat pump circuit with compres-sion of a single-phase inert gas mixture as refrigerant through centrifugal forces	Process and district heating up to 150 °C and 700 kW	+ Low total pressure losses and thus high efficiency + High flexibility of temperature range
Stirling heat pump (Olvondo, Enerin) TRL = 6–9	Heat pump circuit based on counterclock-wise Stirling cycle	Applications with large temperature lifts and sink temperatures up to 250 °C	+ Environmentally-friendly refrigerant (Helium) + High sink temperatures and large temperature lifts with high COP
Hybrid heat pump (AGO Energie, Hybrid Energy) TRL = 9	Hybrid of compression and absorption heat pump with ammonia-water solution as refrigerant	Process and district heating applications with sink temperatures up to 150 °C	+ Due to mechanical compression, no fossil heat supply required + Flexible operation through regulation of the mixing ratio of the solution
rayton heat pump (DLR) TRL = 4	Heat pump based on the Brayton cycle with air or argon as refrigerant	Process heat up to 500 °C	+ Opens up high temperature ranges + Increased COP due to expander + Environmentally-friendly refrigerant

Fraunhofer IEG based on Wolf (2017); Soroka (2015); International Energy Agency (IEA) (2022b); Nekså et al. (2019); Stathopoulos (2022)

A.4 Analysis of the heat generation costs

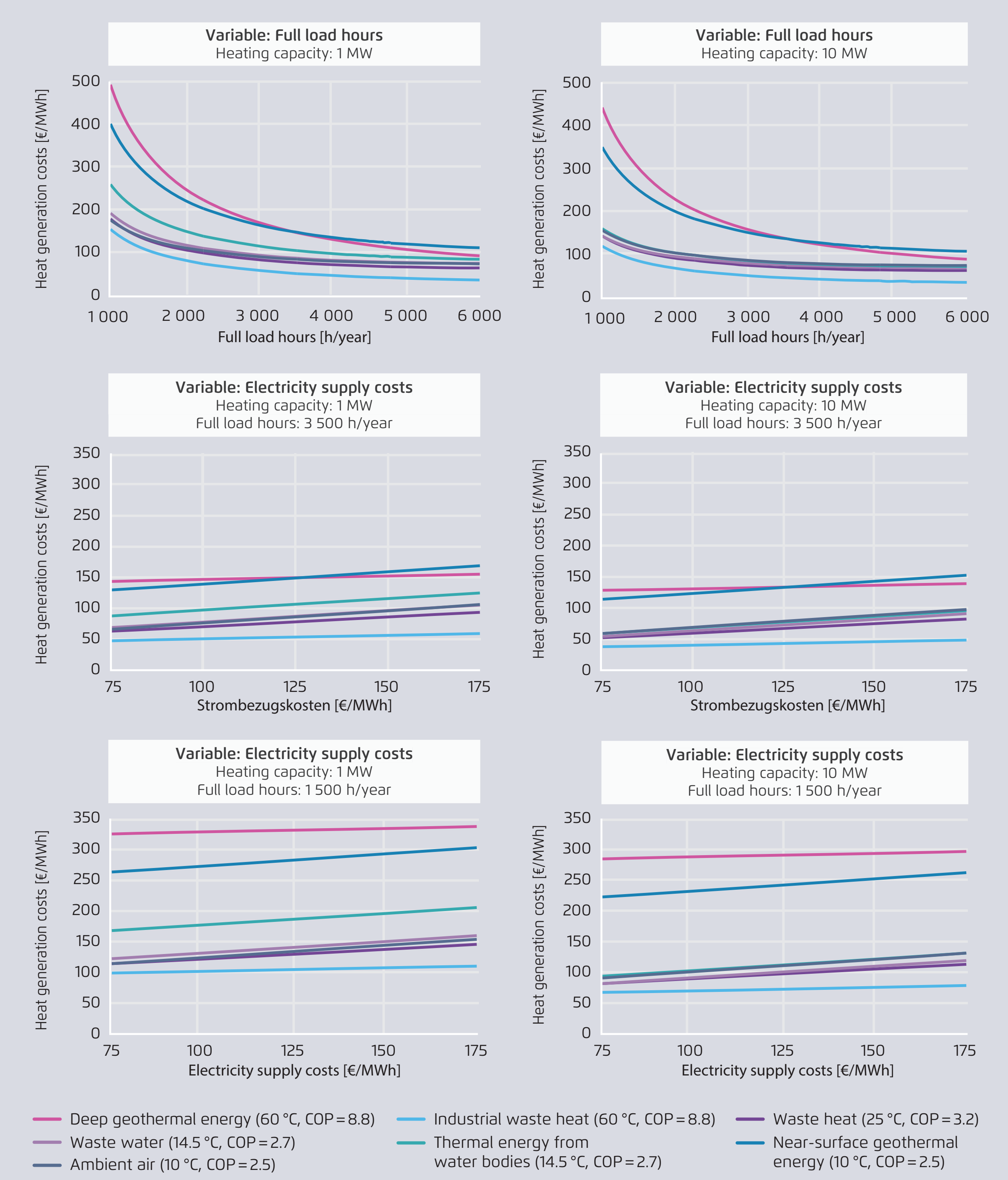
Breakdown of the heat generation costs* for different heat sources with varying full load hours — Figure 44



Fraunhofer IEG (2023) based on VDI guideline 2067. * Calculated using the assumptions made in section 5.5 for a thermal capacity of 10 MW

Unit heat production costs in 2030 for different heat sources with varying full load hours and electricity supply costs, for plants with a heating capacity of 1 MW and 10 MW at a sink temperature of 80 °C

Figure 45



Fraunhofer IEG based on VDI guideline 2067 sheet 1. Calculated without taking subsidies into account.

A.5 Checklist for district heating providers for the planning and implementation of large-scale heat pump projects

Checklist of important issues for large-scale heat pump projects — Table 9

Issues/questions	**Trade-offs/Factors to be taken into consideration (choices/options)**
Financing the development of the strategy and identification of measures	From own resources or with external funding (e.g. BEW Module 1)
Compatibility with municipal heat plan	Early and regular coordination with the local authority, approval authorities and other stakeholders
Need for support from planning offices/consultancies	Higher costs for tendering and awarding of planning and consulting services vs. greater expertise, higher quality and faster turnaround
Funding application for the subsequent implementation of the project	Early decision on the preferred funding framework (BEW Modules 2–4 vs. iKWK tender and EE bonus), taking into account the associated funding criteria, funding level and the permissible implementation period until operational launch.
Which (potential) heat sources can be tapped where	Source-specific and distance-dependent expenditure for access and connection should not exceed achievable COP benefits. In principle, however, all available heat sources should be used and, if possible, those with the best cost-benefit ratio first. Need for early coordination with potential waste heat suppliers (e.g. industry, sewage treatment plants, data centres).
Location under consideration and relevant temperature/ load range of the heat sink	Which (network) area with which network and performance characteristics should and could be supplied by the large-scale heat pump in the future How will the demand for heat develop with increasing progress in renovating buildings? Are technical adjustments to the heat transfer stations planned? (Need for coordination with large district heating customers, e.g. housing associations) Are additional investments in the district heating system required (temperature, hydraulics, optimisation of regulation equipment, pipeline extension and new network connections)? (Minimum network size for BEW Modules 2 and 3 must be considered) Should the design of the large-scale heat pumps focus on achieving higher sink temperatures or a higher COP?
Flow and/or return integration into the district heating system	
Higher temperature vs. higher COP as optimisation goal	
Power, heat generation and flexibility of the large-scale heat pumps? Which compressor technology?	Depending on the temperature, performance and flexibility requirements, different technologies, refrigerants, operating and configuration variants can be considered for the large-scale heat pump assembly. This also influences the cost of operation, maintenance and servicing.

Issues/questions	Trade-offs/Factors to be taken into consideration (choices/options)
A single large large-scale heat pump vs. several smaller large-scale heat pumps	Large pumps have clear unit cost advantages over smaller pumps. However, the latter offer the advantage of standardised planning and approval procedures, and are more flexible and more versatile in use and application.
Functions and design of the heat storage	What functions and time periods must the heat storage facility cover and how will it be constructed (e.g. tank, underground basin, aquifer, borehole, pit water)?
Selection of the site(s)? Land acquisition and urban land use planning required?	Which locations are suitable for the installation of large-scale heat pumps or offer the best conditions? Do building rights and land ownership still need to be acquired?
Requirements for the power supply networks and the power connection	Is an electrcity network connection available and powerful enough? Is it possible to obtain green electricity from renewable energy sources locally or via a direct line?
Relevant regulations and competent licensing authorities? Scope and duration of the approval procedure?	What regulations apply to the project? Which approval authorities are responsible? Which expert opinions are required? How can the approval procedure be speeded up? Is an early start to construction necessary or advisable in order to meet deadlines and climate protection targets?
Total investment requirement and resulting heat production costs	What is the total investment requirement? What heat production costs result on the basis of different scenarios for the development of the electricity procurement costs and O&M expenses?
Effects on district heating supply contracts and prices	What adjustments are necessary to the price formulas and supply conditions in the district heating supply contracts (e.g. indices for linking to electricity procurement costs)? What effects does the project have on future district heating prices (also in comparison to other alternatives, such as e.g. business as usual or green hydrogen)?
Financing the investment with the aid of subsidies (BEW or iKWK)?	How high is the potential profitability shortfall that may need to be closed with the help of subsidies (CAPEX and/or OPEX subsidies under the BEW or KWKG grant via iKWK tenders)?
Management of the construction work and design of the commissioning procedure (EU tender)?	Is the involvement or commissioning of a construction project manager or a general contractor possible and sensible (depending on the complexity and size of the project)? Does the contract value exceed the threshold for EU tenders? Does the tender outcome meet expectations?
Detailed planning, delivery deadlines, site and construction supervision	What adjustments result from the outcome of the tendering for the detailed planning for the construction work? What effects do longer approval procedures and delivery times or staff shortages have on project implementation?

Fraunhofer IEG (2023)

Publications by Agora Energiewende

IN ENGLISH

Transitioning away from coal in Indonesia, Vietnam and the Philippines
Overview of the coal sector with a focus on its economic relevance and policy framework

Hydrogen import options for Germany (Summary)
Analysis with an in-depth look at synthetic natural gas (SNG) with a nearly closed carbon cycle

Briefing on the Europe-China Workshop on Carbon Markets, with coverage of the EU CBAM and carbon asset management

Ensuring resilience in Europe's energy transition
The role of EU clean-tech manufacturing

Levelised cost of hydrogen
Making the application of the LCOH concept more consistent and more useful

Decarbonisation in State-Owned Power Companies
Briefing from the workshop on 28–29 September 2022

From coal to renewables
A power sector transition in Kazakhstan

12 Insights on Hydrogen – Argentina Edition

Breaking free from fossil gas
A new path to a climate-neutral Europe

How Europe can make its power market more resilient
Recommendations for a short-term reform

Argentina as a hub for green ammonia
A forward-looking development strategy for addressing the global energy and climate crises

Overview of China's Energy Transition 2022
Chapter on Oil

The driving forces behind the green transition in Europe and South Korea
A comparison between the European Green Deal and the Korean Green New Deal

All publications can be found on our website: www.agora-energiewende.org

Publications by Agora Energiewende

IN GERMAN

Haushaltsnahe Flexibilitäten nutzen
Wie Elektrofahrzeuge, Wärmepumpen und Co. die Stromkosten für alle senken können

Der CO_2-Preis für Gebäude und Verkehr
Ein Konzept für den Übergang vom nationalen zum EU-Emissionshandel

Wasserstoff-Importoptionen für Deutschland
Analyse mit einer Vertiefung zu Synthetischem Erdgas (SNG) bei nahezu geschlossenem Kohlenstoffkreislauf

Windstrom nutzen statt abregeln
Ein Vorschlag zur zeitlichen und regionalen Differenzierung der Netzentgelte

Roll-out von Großwärmepumpen in Deutschland
Strategien für den Markthochlauf in Wärmenetzen und Industrie

Ein neuer Ordnungsrahmen für Erdgasverteilnetze
Analysen und Handlungsoptionen für eine bezahlbare und klimazielkompatible Transformation

Rückenwind für Klimaneutralität
15 Maßnahmen für den beschleunigten Ausbau der Windenergie

Klimaneutrales Stromsystem 2035 (Zusammenfassung)
Wie der deutsche Stromsektor bis zum Jahr 2035 klimaneutral werden kann

Die Energiewende in Deutschland: Stand der Dinge 2022
Rückblick auf die wesentlichen Entwicklungen sowie Ausblick auf 2023

Volle Leistung aus der Energiekrise
Mit Zukunftsinvestitionen die fossile Inflation bekämpfen

Durchbruch für die Wärmepumpe
Praxisoptionen für eine effiziente Wärmewende im Gebäudebestand

Schutz in der fossilen Energiekrise
Optionen für Ausgleich und Entlastung

Klimaneutrales Stromsystem 2035
Wie der deutsche Stromsektor bis zum Jahr 2035 klimaneutral werden kann

All publications can be found on our website: www.agora-energiewende.de

316/03-S-2023/EN

About Agora Energiewende
Agora Energiewende develops scientifically sound, politically feasible ways to ensure the success of the energy transition – in Germany, Europe and the rest of the world. The organisation works independently of economic and partisan interests. Its only commitment is to climate action.

This publication is available for download as a PDF under this scan code.

Agora Energiewende
Anna-Louisa-Karsch-Straße 2
10178 Berlin | Germany
Phone: +49 (0)30 700 14 35-000
www.agora-energiewende.de
info@agora-energiewende.de

Agora Energiewende