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IEA DHC

INTERNATIONAL ENERGY AGENCY
TECHNOLOGY COLLABORATION PROGRAMME ON
DISTRICT HEATING AND COOLING



ANNEX TS7 FINAL REPORT AND GUIDEBOOK

INDUSTRY-DHC SYMBIOSIS

A SYSTEMIC APPROACH FOR HIGHLY INTEGRATED INDUSTRIAL AND THERMAL ENERGY SYSTEMS

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Industry-DHC Symbiosis

A systemic approach for highly integrated industrial and thermal energy systems

Final Report of the IEA DHC Annex TS7 & Guidebook

Main Authors

Schützenhofer C (AIT), Schüwer D (Wuppertal Institute), Ozen O (TU), Kohne T (TU), Sorknæs P (AAU), Yuan M (AAU), Magni Johannsen R (AAU), Nielsen S (AAU), Habib J (AAU), Golshanfard A (AAU), Müllehner R (EI JKU), Jauschnik G (EI JKU), Takacs A (EUROHEAT), Marx N (AIT), Pfleger J (AEE), Schmidt R (AIT), Cozzini M (EURAC).

Contributing Authors

Corscadden J, Jervis C E (EUROHEAT), Gudmundsson O (Danfoss), Bucherer M, Reuter S (AIT), Marx N (AIT), Gruber-Glatzl W (AEE), Cozzini M (Eurac, Italy), Novati G (Pol Mil, Italy), Yuan M (AAU, Denmark), Block S, Holtz G, Kurwan J, Samadi S, Scholz A (Wuppertal Institute, Germany).

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Edited by Elisabeth Mrakotsky-Kolm

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1. EXECUTIVE SUMMARY

This work provides a systematic overview of methods for achieving excess heat use in industry. For excess heat to be utilized in district heating, several factors must be aligned and carefully coordinated.

Excess heat is defined here as unused thermal energy resulting from human activities, typically, because of industrial, chemical, or biological processes, released into air or water without recovery. We focus exclusively on anthropogenic sources such as data centres, manufacturing, and wastewater treatment. Natural sources (e.g., geothermal, solar, ambient air/water), sole energy conversion (e.g., CHP plants, waste incineration, boilers), and nuclear power are excluded for the topic of this work. Moreover, research explicitly aimed at improving the efficiency of such systems is also not considered.

The IEA DHC Annex TS7 was established as an international collaboration platform under the supervision of the IEA DHC – the International Energy Agencies technology cooperation programme for district heating and cooling. The platform worked from 2021 to 2025 and included over 45 experts from the field. This guidebook is the main outcome of this work and summarises the **core findings**.

From the **best practices in section 2** we conclude that, first, trust between parties sets the cornerstone necessary to overcome the main obstacle, divergent capital structure, and weighted average costs of capital, demanding different profitability by industry and energy service companies. In other words: dividing up profits in a way that all parties perceive as a fair deal is key for such multi-year implementation projects. Second, non-technical benefits are essential in selling business cases to decision makers. These include frugality being part of company core values and communication narrative. When such conservation efforts align with a company's understanding of its purpose, profitability considerations can be overcome to a reasonable extent and the necessary momentum and leadership for implementation can build up. On the industry side, this includes key personnel support facing opportunity costs in time spent on selling such non-core business activity to management. Third, strong enabler are obligatory implementations as can be observed from China, where local governments have substantial influence on businesses' pollution reduction efforts.

From screening **methodologies for assessment of heat utilization potential** (section 3), we learn that there is about 2,860 TWh per year of excess heat accessible in the EU, much of which could be reused. To put this into perspective, the EU's total energy demand for heat and hot water in residential and service sector buildings was 3,180 TWh per year in the EU27+UK in 2021. (Danfoss, 2023). The excess heat from heavy industrial sites in the EU amounts to over 267 TWh a year (more than the combined heat generation of Germany, Poland and Sweden in 2021, (Euroheat, 2025)). Considering only excess heat sources over 95°C and at a distance within 10 km of existing district heating infrastructure, there is a potential of 64 TWh or 12% of energy supplied to EU district heat infrastructure annually (Danfoss, 2023). From a current perspective, there is a lot of excess heat unused in industry see the composition of industrial process heat in the EU in Figure 1. How this potential develops is assessed in section 4.3.

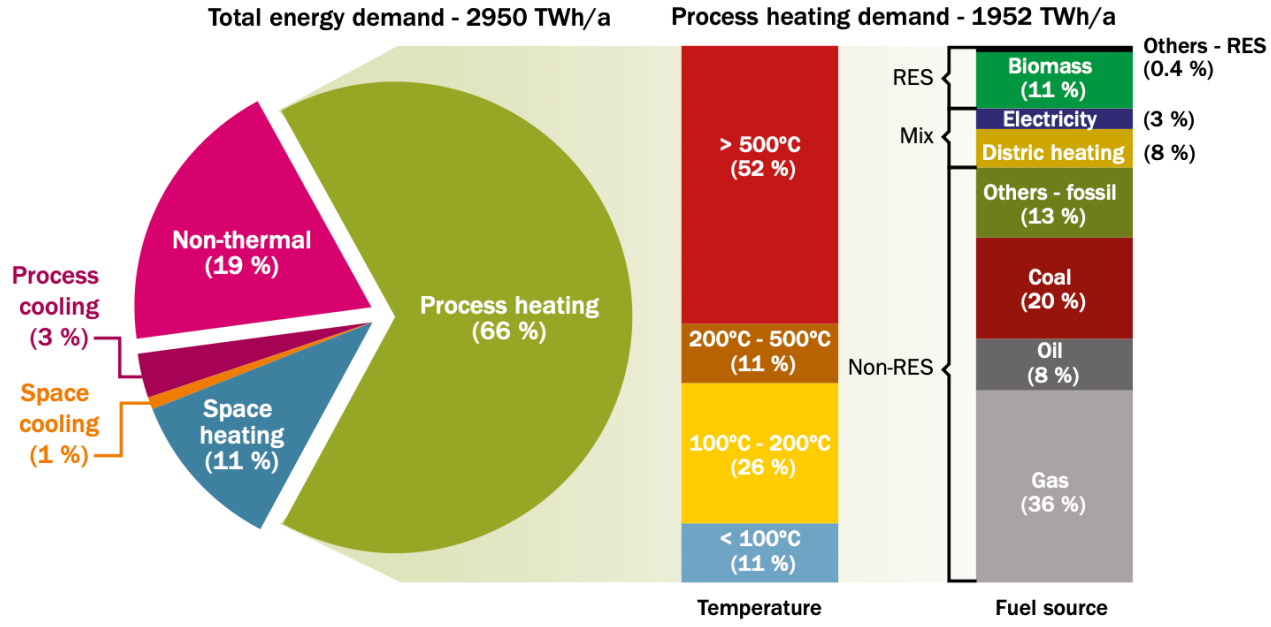


Figure 1: Composition of industrial process heat, temperature level, share of EU total final energy demand, Source: Boer et al. 2020

According to the ReUseHeat EU project results, the biggest excess heat source in urban areas is sewage water (42%), followed by buildings (service sector 19% and residential 8.8%) and data centres (23%). Only 2.4% of the heat demand could be met by metro systems, 4.3% by food retail and 0.32% by food production facilities. (Lygnerud et al., 2022)

Section 4 presents an aggregated view on publications on industry – DHC implementation.

Section 5 presents key aspects of successful business models. These were identified from best practices and verified by successful implementation. We find as a central key success factor for implementation the presence of motivated individuals with a strategic or technical vision and communication skills for building trust to bridge differences in economic and commitment duration expectations of the main parties.

2. BEST PRACTICE EXAMPLES

Authors: Marx Nico (AIT), Takács András (EUROHEAT), Pfleger Jasmin (AEE Intec)

The integration of industrial excess heat into district heating and cooling (DHC) networks represents a critical opportunity to enhance energy efficiency and decarbonize heating systems. The first chapter of the IEA DHC Annex TS7 aims to identify best practice examples that demonstrate synergy effects between industry and DHC networks. It demonstrates successful excess heat recovery and utilisation, while highlighting the associated technological, financial and organisational challenges.

2.1 METHODOLOGY FOR COLLECTING BEST PRACTICES

To identify relevant best-practice examples, a structured data collection approach was applied. A standardised template was developed to gather key data and information. This template included the following elements:

- **General project information:** Project name, timeframe, stakeholder involvement (including ownership structure, company size, staff, and energy consumption).
- **Technical specifications:** Main technologies used, renewable or excess heat sources, rated power, peak MW, temperature levels, network length, distance to nearest DHC network main pipe.
- **DHC network details:** Size (peak MW, GWh/a), share of energy used for space heating, number of households supplied, primary energy carriers supplemented, heat generation mix.
- **Cooperation and risk assessment:** Duration of negotiations, bottlenecks encountered, risk factors, mitigation strategies, and key contractual aspects (investment, ownership, pricing, organizational structure).
- **Financial and economic aspects:** Business models, financing structures, total investment, and available subsidies.
- **Challenges and solutions:** Technical, financial, and regulatory barriers faced and strategies to overcome them.
- **Replication potential and lessons learned:** Key takeaways and recommendations for scaling similar initiatives.

The selection was carried out by the TS7 participants. Focus was put on excess heat recovery from industrial activities, with additional consideration of DHC-to-industry options. The scope was extended beyond traditional manufacturing industries to include excess heat recovery options from commercial and tertiary activities, such as data centres, metro systems, wastewater treatment plants, and service sector buildings.

A total of 20 best-practice examples were received and analysed, covering a wide range of renewable and excess heat applications across different European countries. The data was collected via a standardized case study template and gathered via the *Industry DHC Symbiosis – Best Practices* survey (Own survey, 2025). Selected cases were presented online on the Euroheat & Power Knowledge Hub (Euroheat & Power, 2025).

2.2 OVERVIEW OF BEST PRACTICES

The collected case studies illustrate diverse approaches to integrating renewable and excess heat sources into DHC networks. The cases selected here each present distinct characteristics to be considered as lessons learned.

2.2.1 WASTEWATER TREATMENT PLANTS

Wastewater treatment plants are a significant source of excess heat. In the EU, the total accessible excess heat potential is 318 TWh per year. Lygnerud et al. (2022) identified 2617 such plants in the EU28, most of which are located near dwellings.

One best practice case study was performed in Berlin, Germany. This case study uses excess heat from the Ruhleben sewage treatment plant, operated by Berliner Wasserbetriebe, to contribute to decarbonise the network. Heat pumps are used to raise the temperature of the sewage water from approximately 15°C to the required district heating temperature of 90°C, making it viable as an energy source. This source of excess heat will provide heat to around 45,000 households and play a role in electricity production via the nearby CHP plant. This plant is one of the largest examples of excess heat utilisation from wastewater in the EU. (Euroheat & Power, 2025).

2.2.2 DATA CENTRES

In 2022, data centres in the EU27+UK consumed around 60 TWh of electricity, accounting for approximately 3% of the region's total electricity demand (European Commission, 2024a). The EUDCEAR (EU Data Centre Energy Audit and Reporting) project, which evaluates data submitted under the Energy Efficiency Directive (EED), currently lists 2161 data centres, 770 of which have reported energy and sustainability indicators (European Commission, 2024b). However, only around 6% reported any reuse of excess heat, with an average outlet temperature of 25°C (European Commission, 2024a), indicating significant untapped potential in view of the obligation to supply excess heat under the EED.

A data centre excess heat project in Amsterdam (best practice example 17 in Table 1) will supply 15,000 households via a district heating network. The project will be equipped with a high-temperature heat pump prototype that upgrades the initial 35°C excess heat to 85°C in summer and up to 120°C in winter. With this business model, the project represents an advanced example of excess heat utilisation and

will be the first high-temperature heat pump in the Netherlands to operate at temperatures of up to 120°C (Euroheat & Power, 2025).

2.2.3 COMMERCIAL BUILDINGS / AIR CONDITIONING

Commercial and service sector buildings such as hospitals, offices and shopping centres are characterised by simultaneous cooling and heating demands and therefore represent a highly relevant source of recoverable excess heat in urban areas.

Best practice example 4 (see Table 1) is located at the Hospital Universitario Severo Ochoa in Madrid, Spain, and demonstrates excess heat recovery from electric chillers in a healthcare facility. The heat pump captures heat from the outlet water of the chillers' condensing circuit (25–35°C) and increases its temperature to 50–55°C. This heat can then be injected into the local district heating network. Previously, this heat was dissipated via cooling towers, indicating a clear efficiency gain through recovery. (Own survey, 2025).

2.2.4 INDUSTRIAL PROCESSES

Best practice 1 (see Table 1) is an industrial excess heat project in Vienna, Austria, which uses excess heat from the **baking process** and CHP to supply 1 MW to a district heating system serving 600 households. This project demonstrates the economic viability of excess heat reuse in this context. (Own survey, 2025).

In another project (best practice 12, see Table 1), industrial excess heat from AstaReal's **algae cultivation processes** in Gustavberg, Sweden, is recovered using a compression heat pump to inject the heat into the local district heating network. This model is based on the standardised SamEnergi model and transparent communication, enabling similar projects to be realised. (Euroheat & Power, 2025).

The Nordborg Campus Energy Renovation project at Danfoss A/S in Denmark (Best Practice 10) showcases the effective, large-scale reuse of excess heat in an industrial setting. Since 2007, the campus has reduced its heat demand by 67% by recovering excess heat from building ventilation, process cooling and a data centre, which now supply 51% of the remaining heat demand. The recovered heat is integrated via a low-temperature network using standard, commercially available technologies with short payback times. This project demonstrates the economic and technical feasibility of decentralised excess heat reuse in large industrial facilities and its scalability across multiple sites. (Own survey, 2025).

Hydrogen production via water electrolysis is emerging as a potential future industrial excess heat source for DHC networks. Electrolysers generate low-temperature excess heat in the range of approximately 50 to 80°C, which can be integrated into low-temperature networks or upgraded using

heat pumps. However, large-scale applications are still in early development. No mature best practice cases comparable to the examples above are available yet. (HY2HEAT, 2025)

2.2.5 MINES

Coal regions in Europe present specific challenges related to legacy infrastructure, uncertain subsurface conditions and the transition of former mining regions away from fossil-based energy systems. Mijnwater in Heerlen, in the Netherlands (best practice case 20) uses a system that integrates different energy sources, technologies, and digital tools to provide a flexible energy supply for the city, based on close cooperation between the municipality, the DHC operator and local industrial and commercial heat users. The project implements a thermal source network (TSN), using the former coal mine as a heat source and for underground energy storage, with decentralised heat pumps, bi-directional wells and digital control enabling heat exchange between multiple connected prosumers and consumers. (Euroheat & Power, 2025).

2.3 LIST OF BEST PRACTICE EXAMPLES

This section lists the twenty best practice cases analysed in this study, covering industrial production, wastewater treatment, data centres, commercial buildings, and subsurface sources. Each case is assigned to a heat source category and a qualitative source temperature class following:

- Very Low: below ~15°C
- Low: ~15 to 35°C
- Medium: ~35 to <70°C
- High: 70 to 100°C
- Very High: above ~100°C

Table 1: Best practice examples & links to project web pages

No.	Name & Link	Country	Heat Source Category	Source Temperature Class
1	Excess heat from Manner Sweets Factory - Vienna, Austria	Austria	Industrial production	High
2	LIFE4HeatRecovery in - Ospitaletto, Italy	Italy	Industrial production	Low
3	Leerstoel Warmtenetten project - Antwerp, Belgium	Belgium	Mixed urban sources	Low to High
4	Hospital Heat Recovery - Madrid, Spain	Spain	Commercial buildings and cooling	Low
5	Excess heat of data centre for Hospital - Vienna, Austria	Austria	Data centres	Low
6	Wastewater treatment plant excess heat - Gleisdorf, Austria	Austria	Wastewater	Very Low
7	DELTA energy laboratory for technologies in application - Darmstadt, Germany	Germany	Industrial production	Low
8	Heat recovery from data centres - Brunswick, Germany	Germany	Data centres	Low
9	Biomass Plant Excess heat Utilisation Project – Kindberg, Austria	Austria	Industrial production	Very High
10	Danfoss Nordborg Campus Energy Renovation – Nordborg, Denmark	Denmark	Industrial production	Low to Medium
11	Marzahn/Klinberg data centre - Berlin, Germany	Germany	Data centres	Low
12	Fjärrvärme, Samenergi Excess heat Project from Algae Cultivation - Gustavberg, Sweden	Sweden	Industrial production	Low
13	Wrompa project: heat pump based on raw sewage - Wrocław, Poland	Poland	Wastewater	Very Low to Low
14	Reuter sustainable heat and power from wastewater - Berlin, Germany	Germany	Wastewater	Low
15	ReUseHeat project overview	EU	Mixed urban sources	Low
16	Life4Heat Recovery project overview	EU	Mixed urban sources	Low
17	Excess heat from data centre - Amsterdam, The Netherlands	Netherlands	Data centres	Low
18	Smart cooling – Berlin, Germany	Germany	Commercial buildings and cooling	Medium
19	Wastewater excess heat project - Vienna, Austria	Austria	Wastewater	Low
20	Mine water excess heat project - Heerlen, the Netherlands	Netherlands	Mines and subsurface	Low

2.4 KEY INSIGHTS AND LESSONS LEARNED

An analysis of all collected cases shows that successful excess heat recovery projects share a common set of enabling factors. These factors span technical, economic, organizational, and regulatory dimensions and determine whether a project can be implemented and operated reliably.

2.4.1 TECHNICAL CONDITIONS

Projects are most successful when the excess heat source is continuous, predictable, and available throughout the year. The stable operation of heat sources such as data centres, wastewater treatment plants, and industrial processes allows for a reliable baseload supply to district heating networks. Heat pumps are a key enabling technology because they bridge the temperature gap between low-grade excess heat (typically 15–40°C) and the supply temperatures required by district heating networks (often 70–100°C). The correct sizing and operation of heat pumps are essential for achieving high efficiency and low operating costs. The distance between the source and the sink has a significant impact on economic viability. Shorter connections as well as the integration into existing low-temperature district heating systems or TSNs operating at very low temperature levels below 60°C, reduce technical losses and investment requirements. Successful projects often rely on standardised, technical interfaces, such as modular heat exchanger units or prefabricated heat pump modules. They are reducing design time and facilitate replication in other locations. The core question is whether the heat source is technically suitable for integration into an existing or planned low-temperature network.

2.4.2 ECONOMIC FEASIBILITY

A clear and transparent business model is one of the most important factors for success. The cases demonstrate various potential ownership and investment structures, involving energy utilities, industrial site owners, municipal partners, and energy service companies. It is crucial to define who will invest, operate, and own the recovered heat from the beginning. Long-term supply contracts between the heat supplier and the district heating operator (typically lasting 10 to 20 years) ensure revenue stability and provide the confidence required for investment. Most projects have benefited from public support schemes, such as national or EU funding programs, including BEW in Germany, LIFE at EU level and the Austrian environmental support scheme. Without such support, many projects would not have reached financial viability. Most successful projects aimed for a payback period of less than five years, which has proven important for attracting investors and gaining internal company approval. The key question is whether the business model is financially sound and supported by stable, long-term agreements.

2.4.3 ORGANISATIONAL STRUCTURE

Implementation is easier and more reliable when the process is coordinated by a dedicated intermediary or energy utility. Actors such as Wien Energie, Vattenfall, and Bioenergie Austria act as facilitators between excess heat providers and district heating network operators. Clear roles and responsibilities must be defined from the outset, covering operation, maintenance, data sharing, and risk allocation. Involving partners with proven experience in district heating planning and industrial integration helps avoid costly redesigns and delays. The key question is whether there is an organisation that will assume overall responsibility and ensure coordination between all parties.

2.4.4 REGULATORY AND PERMITTING ASPECTS

A supportive regulatory environment is a prerequisite for scaling excess heat recovery. The current European framework already provides a basis through the Renewable Energy Directive (RED III) and the Energy Efficiency Directive (EED III), which both recognise excess heat and cold as usable energy and call on Member States to promote their integration into district heating and cooling systems. Successful countries have implemented these provisions by treating excess heat as a renewable or equivalent energy source, allowing it to qualify for national renewable energy targets and incentive schemes. Permitting procedures need to be predictable and streamlined, since unclear responsibilities across water, environmental and construction authorities often delay implementation. Standard contractual frameworks, as used in the SamEnergi model in Sweden or in the LIFE4HeatRecovery project, help to reduce negotiation time and legal uncertainty. Early dialogue with local authorities shortens approval processes and builds mutual understanding of technical and environmental benefits. The key question is whether national implementation of EU legislation provides clear legal and administrative conditions that enable quick and reliable project approval.

2.4.5 SOCIETAL AND STRATEGIC EMBEDDING

Projects are more likely to be accepted when they form part of a municipal or regional energy strategy. Integrating them into city heat plans ensures they align with long-term decarbonisation objectives and helps to mobilise political and public support. It is important to communicate the benefits, such as CO_2 savings, local job creation, and regional added value, to gain local acceptance. Visible demonstration projects, such as Danfoss Nordborg in Denmark and Minewater Heerlen in the Netherlands, provide strong examples for replication. The key question is whether the project is embedded in local energy planning and supported by the relevant stakeholders.

2.4.6 CROSS-CUTTING TECHNOLOGICAL INSIGHTS

In all cases, large-scale heat pumps emerged as the key technology for integrating low-grade heat. Many projects also combine multiple sources or incorporate thermal energy storage to balance the

temporal mismatch between supply and demand. Digital monitoring and smart control systems enhance performance, reliability, and transparency. Continuous data collection allows system operation to be optimised and provides evidence for future expansion.

2.4.7 SUMMARY OF COMMON SUCCESS FACTORS

Case studies from across Europe show that the successful integration of excess heat depends on several technical, financial, and institutional conditions:

- a stable and continuous heat source,
- a properly dimensioned heat pump,
- short connection distance,
- engaged intermediary or utility partner,
- clear and fair business model,
- access to funding support,
- regulatory clarity and standardised contracts,
- and integration into municipal energy strategies.

Lessons from best practice case studies show that, as soon as these fundamental elements are in place, excess heat recovery can be both technically mature and economically attractive.

2.5 REFERENCES CHAPTER 2

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3. METHODOLOGIES FOR ASSESSING EXCESS HEAT POTENTIALS

Authors: *Peter Sorknæs (AAU), Meng Yuan (AAU), Rasmus Magni Johannsen (AAU), Steffen Nielsen (AAU), Junaid Ahmed Habib (AAU), Aminabbas Golshanfard, (AAU).*

Contributing authors: Chapter 3.3: Marco Cozzini, Giovanni dalle Nogare, and Rosanna Paradiso

This chapter presents methods for assessing excess heat potentials for district heating (DH), highlighting the range of available approaches depending on local data and resources.

The goal is not to provide an exhaustive overview, but to illustrate the diversity of methods, their typical applications, and to inspire further analysis. The choice of methods depends on factors such as the analysis objective, data availability, and tools at hand. Hence, there is not a universally “best” approach, as suitability varies by context.

3.1 METHOD FOR IDENTIFYING RELEVANT PUBLICATIONS

While methods for identifying excess heat for DH are not new, they have gained increasing attention in research. To show this development, a systematic literature review in the field has been carried out. The goal is to show the changing focus of research in the field, with a focus on some of the prevailing methods for assessing excess heat potentials for DH. We trace the historical development of these methods, highlight key research areas, both past and present, and identify gaps in scientific literature.

The literature review is carried out using the Scopus online database of scientific literature. As terminology varies across studies, with “excess heat,” “surplus heat,” and “waste heat” often being used interchangeably, all these variants were included in the literature search. For consistency, in this report the term “excess heat” is used throughout. The search was also limited to only looking at papers within the topics of Energy, Engineering and Environmental studies, and to only including publications tagged with DH. This yielded 1,484 documents.

For each document, the title, abstract, and full text were reviewed by the authors and rated as either highly relevant, somewhat relevant or not relevant. Relevance was based on whether the study presented or applied a method for assessing excess heat potential for DH. Of the 1,484 documents the papers were rated as follows:

- **Highly relevant (197 documents):** Presented and applied specific methods for excess heat assessment.
- **Somewhat relevant (159 documents):** Referenced or discussed excess heat assessments indirectly, often in the context of policy or business models.
- **Not relevant (1,121) documents:** Mentioned DH or excess heat only tangentially or not at all.

The focus here is on the highly relevant papers, and so the remainder of this chapter focuses on the 197 highly relevant studies.

3.2 QUANTITATIVE PUBLICATIONS ANALYSIS

Looking at all the 1,484 documents as well as the 197 highly relevant documents, Figure 2 shows the number of studies published each year between 1976 and 2023. It is evident that excess heat received increasing attention in literature over the years. After 2015, the number of highly relevant publications started to significantly increase in publications per year. For the total of 1,484 publications, an increased interest could be recognized earlier, around 2010, but there was also a significant increase after 2015.

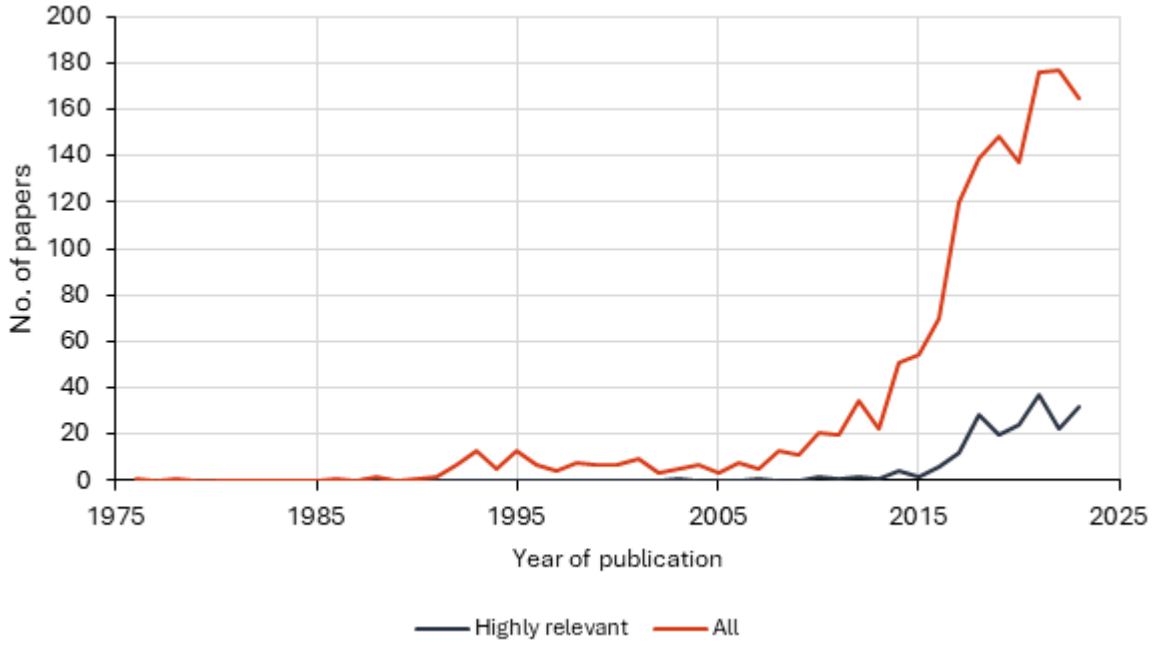


Figure 2: Year of publication of identified highly relevant papers.

Understanding where this type of publications is mostly coming from can highlight if the study of methods for identifying excess heat for DH is a global occurrence or specific for some regions of the world. This can be done by analysing the listed organisational affiliation of the authors of the publications. Figure 3 shows the number of publications per country, with at least one author affiliated with an institution in that country. This means that if several authors of the publication come from the same country it will still only be counted as one in this overview. If authors from several countries are co-authoring, then the publication will be counted several times. It is clear from the figure that most of the highly relevant studies are carried out by European and Chinese authors, with China being the single most represented country. For Europe, authors are especially located in Germany, Denmark and Sweden, though also Southern European countries are well represented, such as Austria and Italy. Outside of China and Europe, Japan is the most represented country by author affiliation.

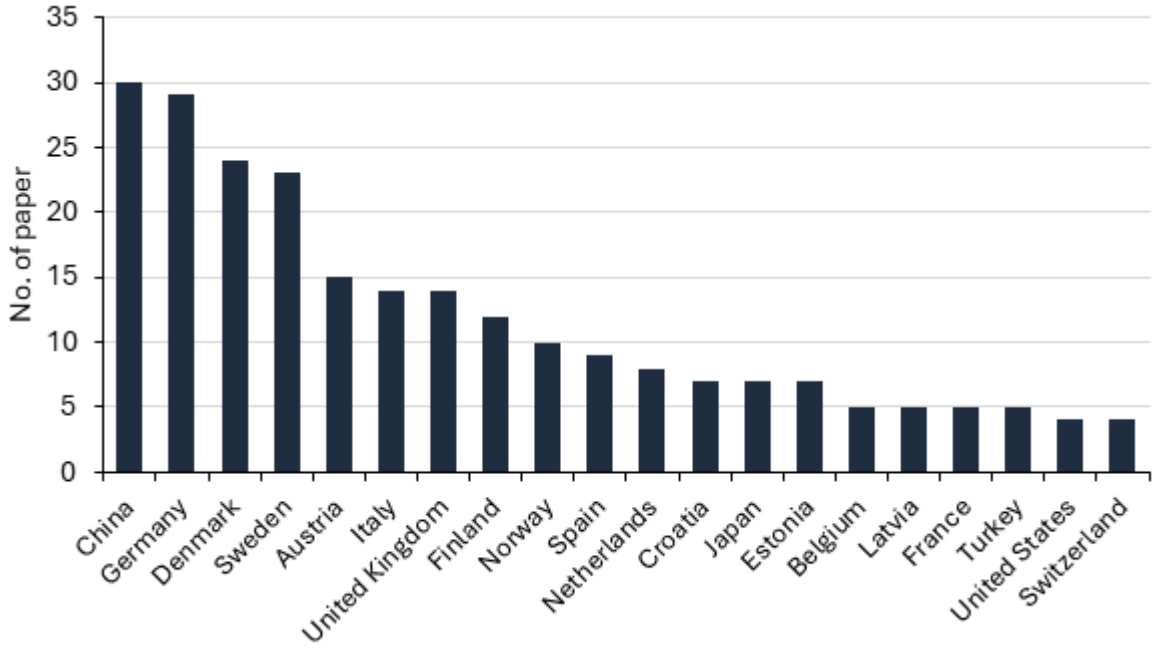


Figure 3: Publications by author affiliations.

Excess heat can origin from a slew of different sources. While reviewing all the publications, they were categorized based on the source of the analysed excess heat. Looking at the result of this categorization, four different sources look to have received most attention. These are industries, datacentres, wastewater/sewage, and Power-to-X (PtX). Figure 4 shows how the focus on different excess heat sources has changed over time since 2010. The other category includes e.g. supermarkets, hospitals, and metros. From the figure it is clear, that earlier studies focused on methods for identifying excess heat potentials from industrial processes, where after 2015 datacentres and wastewater/sewage received increased attention. A few publications referred to PtX after 2015, but only starting from 2022 multiple publications per year were related to identifying excess heat potentials from PtX.

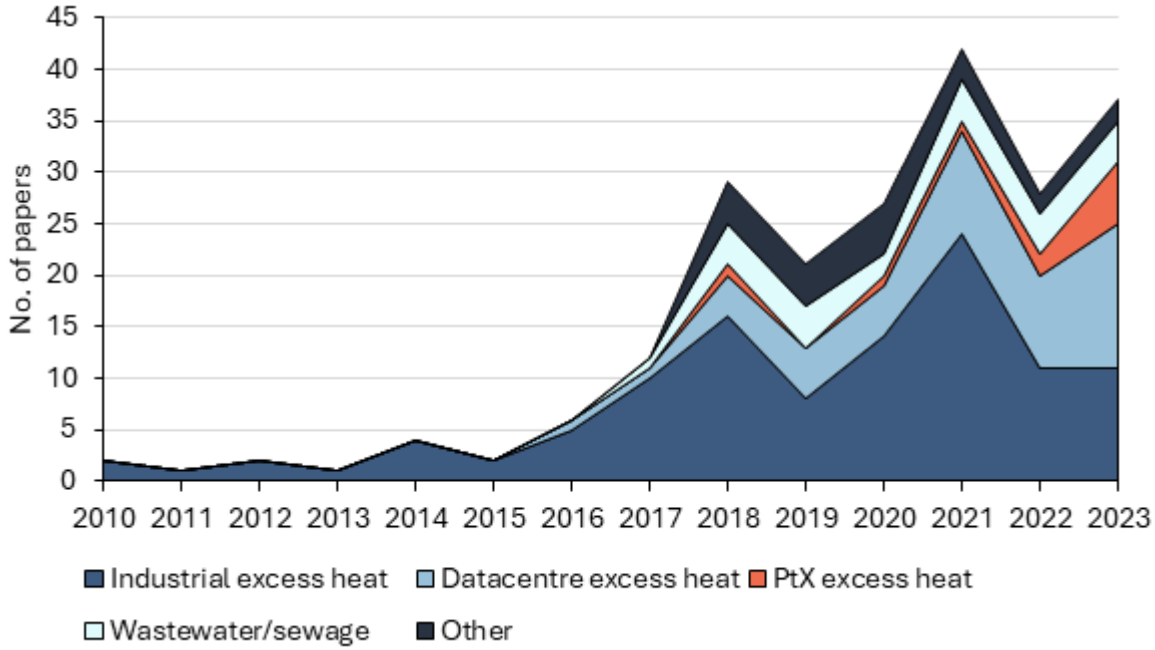


Figure 4: Main source of excess heat identified in studies.

Identifying excess heat potentials for DH can be done on many different levels of scale. While reviewing the publications they were categorized based on the geographical scale of the study. In the publications, excess heat estimates were done on very different geographical scales. This different scope originates from local studies looking at specific projects for a specific potential utilisation case or for a specific city with several potential sources for excess heat. However, continent-wide estimates were found, though typically mostly for the European Union (EU), where statistical data across different countries are collected and organised in a similar fashion. The different geographical scales of applying the method for excess heat potentials are shown in Figure 5. In the figure, the category 'European' refers to studies considering multiple European countries. The category 'national' refers to single country studies, but can be of significant size, as in the case of China. 'Regions' refers to parts of a country but can again, in cases of large countries, constitute relatively significant variations in scale. 'City' refers to individual cities, and 'Project' refers to individual projects where e.g. potential excess heat of a specific industrial site is investigated. Like for Figure 5, one study has been counted several times if it includes several geographical scales. Figure 6 clearly shows that most studies were on city and project levels, followed by national and regional levels.

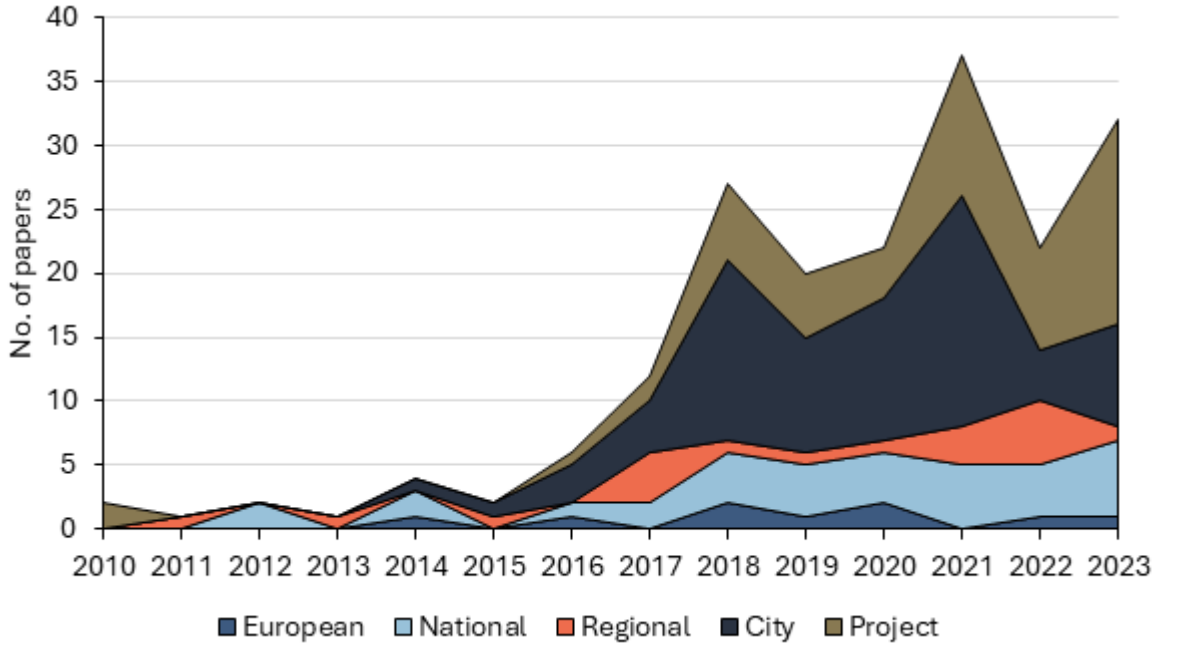


Figure 5: Prevailing geographical scale investigated in studies.

In the review, each publication was also categorized based on the used method. Looking at the methods utilized, two overall methods were predominant, i.e., mapping via geographical information systems (GIS) and the analysis of the operation of the energy system, also known as energy system analysis. While the first is typically focused on the geographical location of the excess heat, the second is typically rather focused on the temporal utilisation of excess heat. Other methods are based on using statistical data without or with limited geographical data as well as interviews and surveys, e.g. with different owners and operators of industries. Figure 6 shows the development in the utilisation of these different methods. Again, like with Figure 3 and Figure 4, one publication can make use of several types of methods in the same study, and thereby can be counted several times. It is clear that energy system analysis is the most typically used method, especially in the most recent years, though many studies are based on GIS.

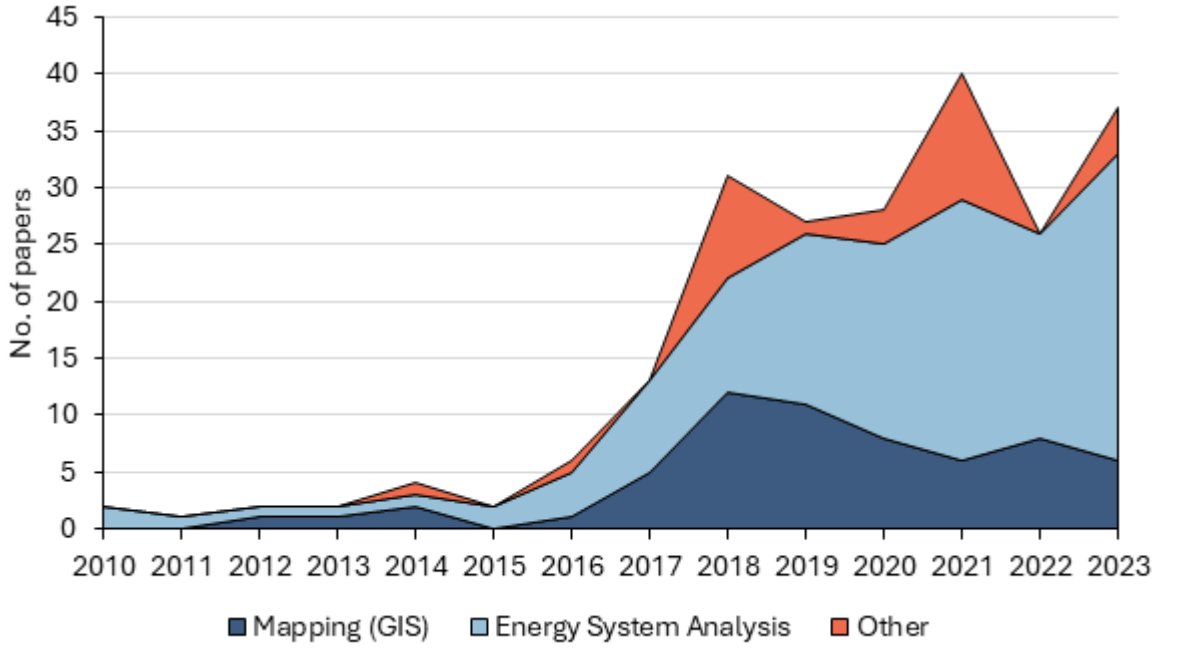


Figure 6: Prevailing methodologies for determining excess heat potentials in studies.

3.3 SYSTEMATIC REVIEW OF ANALYSIS METHODS

Using the categorization from Figure 6, this chapter focuses on structuring and describing various studies that have employed different methods for identifying excess heat potentials. The aim is to illustrate the diverse ways of applying them in practice. The following sections are organized according to the main principal methods used for identifying excess heat potentials.

Examples of using statistical methods are described. This is followed by mapping methods (GIS). Then, different energy system analysis methods are shown, splitting them into two groups, since they are methods focused on modelling of DH systems and methods where more energy sectors are included in sector-coupled analyses. Afterwards, examples of interview and survey-based methods are described. It is important to note that some of these methods can build on other methods (e.g., a model of a DH system might start with a technical potential from a statistical analysis, but then after including the excess heat in the DH system identifies a different realised potential). After describing different studies using different methods, the results of different methods for assessing excess heat are presented.

Figure 8 serves as a visual illustration of the structure of the remainder of this chapter.

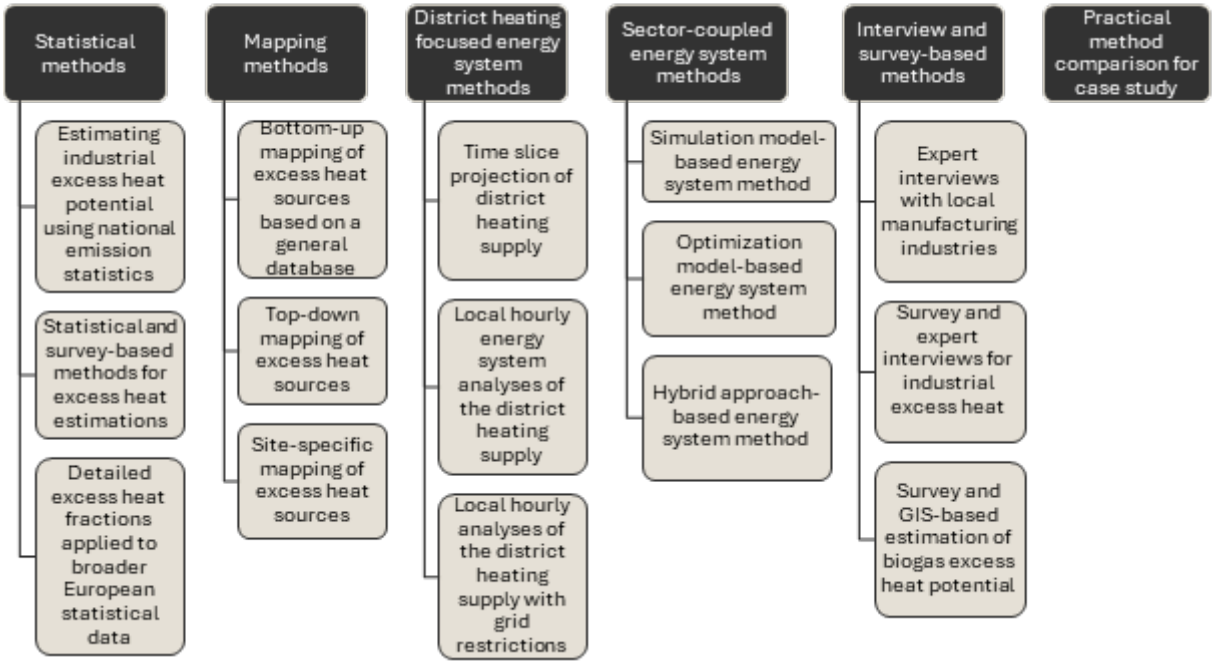


Figure 7: Overview of methods and -categories.

3.3.1 STATISTICAL METHODS

This section presents studies that apply statistical methods and data to estimate excess heat potential. These approaches often rely on national CO_2 emission registers, such as those reported under the European Emission Trading System (ETS), which provide facility-level emissions data that can be linked to thermal energy outputs. Other relevant sources include national energy consumption statistics, employment data (e.g., company size by number of employees), and industrial production figures. These datasets can offer direct or indirect indicators of excess heat generation, enabling researchers to identify and quantify potential recovery opportunities. This section focuses on examples applied to assess industrial excess heat potentials, where such statistical data is generally most available, even though similar methods could in principle be applied also for other sectors and sources of excess heat.

While such statistical methods and data can also be further connected to more detailed spatial analysis, that is not the focus of this section, which focuses solely on the methods for correlating statistical data to physical excess heat quantities. Methods applied in spatial analysis are instead explored in the subsequent section on mapping methods.

ESTIMATING INDUSTRIAL EXCESS HEAT POTENTIAL USING NATIONAL EMISSION STATISTICS

Pelda, Stelter, and Holler (2020) present a method for estimating the potential of integrating industrial excess heat and solar thermal energy into DH systems in Germany. It is an example of an approach

based on statistical data for the estimation of excess heat potential, useful at both city and country levels.

The study estimates excess heat from industrial processes based on CO_2 emissions data reported under the EU-ETS. The primary energy input of industrial facilities is calculated using stoichiometry, and shares of 10%, 20%, or 30% of this input are assumed to be recoverable excess heat. The method focuses on industries such as oil refineries, steelworks, and chemical production, excluding power generation facilities.

The study estimates the theoretical excess heat potential from industrial processes by leveraging CO_2 emission data from the German emissions trading authority DEHSt. The key methodological steps include:

1. Data collection and selection

Industrial CO_2 emissions data were obtained from the German emissions trading authority DEHSt. Only industries within city boundaries and subject to CO_2 emission reporting were considered, filtering out power generation facilities to focus on energy-intensive manufacturing industries such as oil refining, metal production, cement, and chemicals. Cities with more than 100,000 inhabitants were included, with further selection based on data completeness.

2. Primary energy demand calculation

The primary energy input of industrial processes was estimated using stoichiometric calculations, i.e., chemical mass balancing calculations, based on reported CO_2 emissions. The method assumes natural gas as the predominant fuel source (35% share in industry) but provides comparisons for oil and coal. The primary energy demand was derived using combustion equations for methane, carbon, and oxygen, linking CO_2 emissions to fuel use and energy content.

3. Excess heat potential estimation

A percentage of the calculated primary energy input was assumed to be recoverable as excess heat. Three scenarios were considered: 10%, 20%, and 30%. These percentages were based on values from existing literature indicating that 7.4–15% of primary energy input is typically recoverable as excess heat, with higher estimates reflecting optimal conditions (Blömer 2019). Only low-temperature excess heat (<150°C) was considered, as it is more easily integrated into DH without requiring additional high-temperature processing.

4. Future projections (2030 & 2050)

The potential for industrial excess heat in future years was estimated based on projected CO_2 emission reductions and energy efficiency improvements in industry. Greenhouse gas reduction targets of 40% by 2020, 55% by 2030, and 80–95% by 2050 (compared to 1990 levels) were factored into the

projections. The method assumes a 35% increase in industrial energy efficiency by 2050, leading to a decline in absolute excess heat potential.

The study finds a theoretical excess heat potential of 64–193 TWh per year across Germany. The authors argue that this estimate is in line with other estimates for Germany, thus validating the method and results. In certain cities, industrial excess heat could fully supply DH demand, particularly where large industrial emitters are near existing DH infrastructure. Forecasting to 2050, the available excess heat is expected to decrease due to increased industrial efficiency and emission reduction targets, dropping to 12–36 TWh per year under various scenarios.

The study highlights the significant untapped potential of industrial excess heat (and solar thermal energy) in DH systems. However, implementation barriers include a lack of public data on heat quality (temperature levels), economic feasibility uncertainties, and the need for multi-stakeholder cooperation. The research suggests that integrating these heat sources into 4th generation DH (below 70°C) can improve energy efficiency and contribute to decarbonization efforts.

STATISTICAL AND SURVEY-BASED METHODS FOR EXCESS HEAT ESTIMATIONS

The study Luo et al. (2017) focuses on estimating the potentials of low-grade industrial excess heat in Northern China and presents a comprehensive method for investigating these potentials. This section outlines the key methods developed and described in the paper for estimating excess heat potential.

The authors introduce a three-level method designed to meet different objectives for different geographical scales, ranging from macro policymaking to detailed site-specific project development.

The first level involves rough estimation based on macro data. This approach estimates the total amount of available excess heat for the five most energy-consuming industries based on their total energy consumption, as reported in national energy statistics. To validate the results, cooling water consumption data, also available in national statistics, is used to return another excess heat estimate. To calculate the excess heat potential, the reported cooling water consumption is combined with an assumed latent heat of water of 2500 kJ/kg. Both the energy consumption and water consumption-based methods, however, result in similar excess heat estimates of about 800 TWh for the region.

The second level employs a combination of field surveys and questionnaires. Field surveys are conducted on typical energy-intensive industrial factories to gather important parameters influencing excess heat quantity and quality. Questionnaires collect detailed information on production processes, major product outputs, and existing excess heat reuse. This method provides concrete data about low-grade industrial excess heat to support local energy or heating supply planning.

The third level involves detailed in-situ investigations for early-stage preparation of projects. This method focuses on production scheduling, stability of excess heat sources, available space for heat collection equipment, and distances between heat sources and users.

The authors primarily applied various statistical data sources and methods to estimate excess heat potential. For the energy consumption analysis, the authors analysed the energy consumption of the five most energy-intensive industries, which consume about two-thirds of the total industrial energy in China. Data from the National Bureau of Statistics and industry reports provided insights into the proportion of energy consumption that constitutes excess heat. To determine the availability of useful excess heat, the authors adjusted the potentials based on the heating season in Northern China. To determine the excess heat potential based on cooling water consumption, data from the National Bureau of Statistics and the National Development and Reform Commission was used to estimate water consumption used for cooling. This, combined with the latent heat of water, provides a conservative estimate for the excess heat potential.

For detailed regional and site-specific analysis, the authors conducted field surveys and distributed questionnaires to industries in the Hebei province. Data was collected on production processes, energy consumption, and excess heat reuse, which was then supplemented and corrected based on direct measurements and observations. Energy flow models were used to estimate excess heat per unit mass production, providing a comprehensive understanding of excess heat potentials in different industry types. The methods developed by Luo et al. (2017) have been applied in further studies by Ma et al. (2021) for developing a roadmap towards 2035 for how excess heat integration can contribute to reaching the below 2 °C climate target.

DETAILED EXCESS HEAT SHARES APPLIED TO BROADER EUROPEAN STATISTICAL DATA

Papapetrou et al. (2018) present a detailed method for estimating the technically recoverable industrial excess heat potential in the EU. This section outlines the key methods developed and described in the publication for determining excess heat potential.

The method developed by the authors is based on the estimation of excess heat fractions (EHFs) per industry, country, and temperature level. The starting point is a study of the UK industry from 2000 to 2003 (Hammond and Norman 2014), which provided data on heat consumption and recoverable excess heat potential for various industrial sectors. The method involves four main steps.

The first step is to calculate the EHFs for the UK industry during the specified period. The EHFs are determined by dividing the excess heat potential by the heat consumption for each industrial sector and temperature band. This provides a baseline set of EHFs for the UK.

The second step involves adjusting these EHFs to reflect the conditions in other EU countries. This adjustment is made by multiplying the EHFs by a factor that represents the relative energy intensity of each country compared to the UK. Energy intensity values, which correlate energy input with the added value of the final product are obtained from the Odyssee-Mure database. This adjustment accounts for differences in energy efficiency between countries.

The third step updates the EHFs to reflect energy efficiency improvements from the period 2000–2003 to 2015. This is done by calculating the ratio of energy intensity values in 2015 to those from the earlier period for each country and industrial sector. The EHFs are then multiplied by this ratio to obtain updated values for 2015.

The final step involves multiplying the updated EHFs by the heat consumption data for 2015, derived from Eurostat, for each industrial sector and EU country. This results in the estimation of the excess heat potential for 2015, eliminating major uncertainties related to differences in energy efficiency levels between countries and years.

The authors used various statistical data sources and methods to estimate excess heat potential. They analysed energy consumption data from Eurostat and adjusted it to account for process heat consumption in each sector and country. The method also considers the contribution of electricity used for process heating, particularly in energy-intensive industries like iron and steel.

In summary, the method developed by Papapetrou et al. provides a comprehensive framework for estimating industrial excess heat potential in the EU. By combining historical data analysis, energy intensity adjustments, and updated heat consumption data, this approach enables accurate and detailed mapping of excess heat potentials across different industrial sectors and temperature levels. This method supports effective energy planning and the implementation of heat recovery technologies, contributing to significant energy savings and environmental benefits.

3.3.2 MAPPING METHODS

To estimate the industrial excess heat potential for DH integration, it can be relevant to conduct a geographic assessment that locates excess heat sources and quantifies the amount of excess heat available. A geographic assessment enables a spatial analysis of the amount of excess heat available adjacent to existing or potential future DH systems, and in many cases, also estimates the costs of connecting the excess heat sources to the DH system. However, depending on the geographic scope of the analysis and data availability, various approaches can be employed to conduct this geographic assessment. Thus, the following section is divided into three subsections, focusing on bottom-up, top-down and site-specific mapping methods, presenting examples of each of these methods.

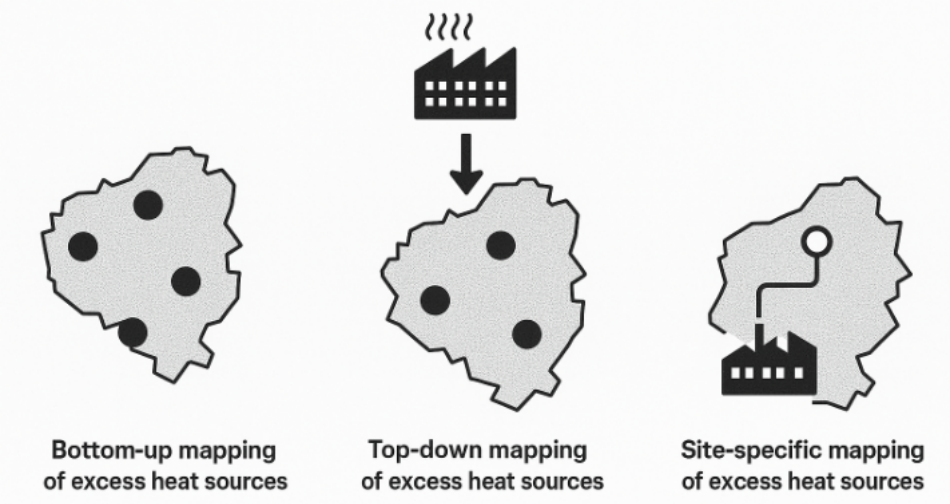


Figure 8: Illustration of spatial mapping methods for excess heat sources for DH (OpenAI 2025)

BOTTOM-UP MAPPING OF EXCESS HEAT SOURCES BASED ON A GENERAL DATABASE

The bottom-up mapping is exemplified by presenting two different publications, (Manz, at al. 2018) and (Persson et al. 2014), see also Figure 8.

Manz et al. (2018) present a method for estimating site-specific excess heat potential based on CO_2 emission registries (NACE and ETS activity). This method, when combined with average process-specific energy demands and excess heat generation estimates, is used to determine excess heat potentials. This mitigates the otherwise very extensive needs for high-resolution spatial and process-specific data in estimating site-specific excess heat potentials.

The approach integrates multiple data sources to estimate excess heat potentials at the facility level:

1. Data collection and matching

Information is sourced from the ETS, the European Pollutant Release and Transfer Register (E-PRTR), and sector-specific databases (e.g., steel, cement, glass, paper). Then, a matching algorithm aligns plant data across databases using indicators such as company name, location, and sector classification.

2. Energy demand and excess heat estimation

Two derived approaches are compared:

- Emission-based estimation: Uses CO_2 emissions and sector-specific emission factors to infer fuel consumption and excess heat.
- Production-based estimation: Uses production capacity and process-specific energy consumption values to calculate fuel demand and excess heat.

For both approaches, excess heat potentials are categorized by temperature levels (>100°C) and estimated for different key industrial processes.

Based on the method presented, the authors provide a georeferenced dataset covering industrial facilities in the EU28, Norway, and Switzerland. Key takeaways from the study include:

- Excess heat potential for the four studied sectors (steel, cement, glass, and paper) is estimated at 63.3 TWh/year, primarily within the 200–500°C temperature range.
- The production-based approach yields more accurate estimates than emission-based methods but requires more detailed data.
- Excess heat potentials vary significantly by country and sector, with cement and steel accounting for the largest shares.

Manz et al. argue that this georeferenced method enables regional assessments of industrial heat integration potential, supporting DH expansion and industrial decarbonization strategies. Further work could include additional expansion of the method to include additional sectors (e.g., chemicals, non-ferrous metals) and lower-temperature heat sources could enhance the comprehensiveness of excess heat mapping.

Another example of a bottom-up approach is Persson et al. (2014) that presents a method for assessing regional excess heat availability and identifying strategic regions for DH integration within the EU27. A broad definition of excess heat is applied, considering thermal power technologies, waste-to-energy, and industrial excess heat. While this categorisation is broader than what we consider in the present study, the methods applied are nevertheless relevant.

Persson et al. integrate public European register data for pollutants and national energy statistics and apply these in GIS mapping and energy system modelling to estimate excess heat potentials and match them with regional heat demands. Key steps are outlined below:

1. Data collection and regional analysis

Excess heat volumes are estimated based on CO_2 emissions from fuel combustion, using data from the European Pollutant Release and Transfer Register. Heat demand estimates are derived from national energy statistics and climate-adjusted population densities at the NUTS3 regional level. DH systems are mapped based on utility and government data.

2. Heat balance and excess heat estimation

CO_2 emissions from industrial and energy sector facilities are converted into primary energy input using sector-specific carbon intensity factors. The study then applies default sector-specific heat recovery efficiency factors to estimate the fraction of primary energy that can be recovered as excess heat. These values, which, according to the authors, are based on literature and empirical data, are assigned per industrial sector:

- Thermal power plants: 50–60%
- Waste-to-energy plants: 60%
- Fuel refineries and steel production: 50% and 25%, respectively
- Non-metallic minerals, chemicals, and food processing: 10–25%

Lastly, the estimated excess heat is compared with total local heat demand to identify areas where recovered heat could replace fossil-based heating.

3. DH integration potential

Regions where excess heat resources align with significant heat demand are classified as strategic heat synergy regions. Clustered urban-industrial areas with high recovery potential are prioritized for DH expansion.

The authors identify 63 strategic heat synergy regions across 16 EU countries, representing 46% of the total EU27 excess heat potential. These regions account for 31% of the total EU building heat demand, presenting significant opportunities for DH expansion. Large urban centres specifically play a crucial role, with regions such as the Ruhr area, Paris, and Milan having the highest heat recovery potentials. The primary sources of excess heat are thermal power plants (70%), industrial processes (26%), and waste-to-energy plants (4%).

The authors conclude that integrating excess heat into DH networks can reduce primary energy demand and improve the efficiency of urban heating systems. Policymakers should prioritize regional heat planning, support infrastructure investments, and include excess heat recovery in EU energy policies to enhance system-wide decarbonization efforts.

3.3.2.1 TOP-DOWN MAPPING OF EXCESS HEAT SOURCES

Bühler et al. 2017 estimates the excess heat potential for 22 industrial sectors in Denmark using top-down methods. The analysis only considers excess heat related to processes; therefore, excess heat from electrical equipment is not included in the estimation. The mapping also considers the various temperature levels of excess heat and energy efficiency measures.

1. Data collection and excess heat estimation

The data used is based on the Danish Central Company Register (CVR), where 2,573 industries were identified. The study employs a combination of different allocation steps to estimate the excess heat potential per industry, depending on the availability of data. First, it utilises actual energy use from site-specific analysis; however, this information was very limited. Second, it utilises the E-PRTR data on CO_2 emissions, which were then used to estimate the primary energy input. E-PRTR only covers large industries, which amounts to around 90 production units or 3.5% of all the analysed industries. Third, the excess heat was distributed among industrial sub-sectors based on the number of employees. This

allocation method covered most industries, but only 35% of the total excess heat (i.e. some large sites were not covered). This last allocation method is what differentiates this study from other studies, but it is also acknowledged that the method is very uncertain and should only be used when more precise data is not available.

2. Spatial analysis of industrial excess heat for DH

The map of industrial excess heat per site is then used in a spatial analysis, where the potential related to DH is identified. The analysis uses a map of existing DH and heat demands per building to identify the heat demand with and without DH. It then further identifies the nearest DH area to each industry and calculates the connection costs as a function of the capacity. Next, an allowed connection cost of 4.17 EUR/MWh is set as a cutoff criterion based on expected DH costs. Finally, the results are summarised on a 5x5 km square grid, showing the excess heat density in the country. The overall results show that there is a theoretical maximum excess heat potential of 3.43 TWh/year, where 1.36 TWh/year can be supplied to DH when considering various criteria, like accessibility and cutoff distance. The 1.36 TWh/year represents approximately 5.1% of the existing DH demand.

3.3.2.2 SITE-SPECIFIC MAPPING OF EXCESS HEAT SOURCES

In a case study in Milano, Italy, Dénarié et al. (2019) estimates industrial excess heat potentials in seven industries. The study employs various methods to estimate the excess heat potential and assess its value.

1. Data collection

The input data is coming from the Autorizzazione Integrata Ambientale (AIA) database, which covers licenses given to companies with a high pollution potential. The database covers both energy consumption and pollutant emissions but also a description of the production processes and temperatures. The database is updated annually for monitoring purposes. Thus, what is used from the database is the final and primary energy per company.

2. Analysis of different approaches to estimate excess heat potential

The study includes a review of different calculation methods for estimating excess heat recovery potentials. It provides detailed descriptions of McKenna et al. (McKenna and Norman 2010), Heat Roadmap Europe (Urban Persson and Werner 2012), Berthou and Bory (Berthou and Bory 2012) and EcoHeatcool (Werner 2006). As the AIA database has the primary energy available, the steps used to estimate this is irrelevant here, and the focus is more on the recovery coefficients per industry type within each Ecoheatcool WP4 study. The coefficients are grouped by the industry sector and recovery percentage: food (5-10%), chemicals (5-12.5%), pulp-paper (2.4-12.5%) and power (25-31%). The specific excess heat recovery coefficients are then applied to the 7 industries in the study.

3. Multi-criteria Decision Analysis (MCDA) related to input data uncertainty

The study applies an MCDA approach to examine the uncertainty in the input data. Here, four different criteria are applied to the AIA data. The first criterion is the data origin, where measured data gets a better score than estimated data. The second criterion pertains to the completeness of the document, encompassing six different criteria for the information included in the AIA. The third criterion pertains to when the data were updated, and the fourth criterion examines homogeneity by comparing differences between years to identify any significant changes. Each of the seven industries then receives a final probability score ranging from 0.38 to 1.00.

3.3.3 DISTRICT HEATING FOCUSED ENERGY SYSTEM METHODS

Studies presented in this section show different approaches to identify the potential utilization of excess heat by modelling and simulating the operation of DH systems. In these studies, other energy sectors are only represented by simplifications, like the electricity system is represented by market prices. Such studies typically include the operation of different DH supply technologies in competition with excess heat sources but can also include grid aspects such as temperature levels and the grid layout as well as heat storage options. They typically include modelling of the DH system on a temporal scale, including the varying heat demand throughout a period, often a year. These studies typically do not directly identify available excess heat sources but rather how much excess heat can be utilized in one or more DH systems and to what cost. They thereby normally build on other methods to identify potential amounts, whereafter these methods can be used to analyse how much of the maximum potential is possible and relevant to utilize. Effects analysed are typically in relation to the change in supply from other sources, such as combined heat and power plants and heat pumps. The effects can also be related to a potential expansion of a DH system, meaning that it can be analysed if utilization of excess heat enables the DH to be more competitive with individual heating supply technologies, and thereby potentially expanding the DH supply of an area.

3.3.3.1 TIME SLICE PROJECTION OF DISTRICT HEATING SUPPLY

A study by Sandvall, Hagberg, and Lygnerud (2021) presents long-term projections for development of heat supply technologies, including the use of excess heat for DH, in four different cities. In this study the researchers wanted to identify future cost-optimal heating supply solutions for four European cities, with a focus on determining the market share of DH in these solutions. The four cities were Madrid (Spain), Nice (France), Berlin (Germany) and Brunswick (Germany).

The analysis included different potential excess heat sources such as high-grade excess heat from industrial processes (80–90°C), as well as low-grade excess heat from data centers (25–35°C), metro stations (5–35°C), service-sector buildings (30–40°C), and sewage systems (8–15°C). Heat pumps were utilized to make low-grade heat viable for DH, with calculations of the different coefficient of performance (COP) of the heat pumps incorporated into the modeling.

The data for excess heat potentials from industrial processes were derived from the Heat Roadmap Europe studies, while information on other sources, including their temporal heat distribution, was based on the European research project ReUseHeat.

In the study four distinct scenarios were developed, reflecting two climate policy frameworks - one based on the Sustainable Development Scenario and the other on the New Policies Scenario from IEA's World Energy Outlook 2017 - and whether investment in large-scale heat pumps were allowed. The TIMES (The Integrated MARKAL-EFOM System) model was then used to optimize heating supply solutions for the period from 2015 to 2052, with simulations performed every five years from 2023 onward. This study's application of TIMES includes both DH supply and individual heating supply technologies, while electricity systems and fuels are modelled exogenously. The objective was to minimize the total cost of meeting the heat demands, with each modelled year divided into eight time slices. Heat demand data and DH distribution costs were sourced from the Pan-European Thermal Atlas (PETA) v4.3.

The results indicate that the utilization of excess heat is constrained by the market share of DH in the cities, with a larger market share of DH allowing more excess heat to be utilized. Berlin exhibited a relatively limited potential for excess heat utilization due to lower availability of excess heat. However, the use of excess heat increases the market share of DH across the cities, with particularly large gains observed in Madrid and Nice, where initial DH market shares were low (1.6% and 16.7%, respectively). In comparison, Brunswick and Berlin have higher existing DH market shares (45% and 43%, respectively).

The integration of excess heat in these systems reduces primary energy consumption and overall system costs, emphasizing its role in advancing more efficient and sustainable urban heating solutions

3.3.3.2 LOCAL HOURLY ENERGY SYSTEM ANALYSES OF THE DISTRICT HEATING SUPPLY

In a study by Doračić et al. (2020) the goal was to analyse what the levelized costs of utilized excess heat would be in different DH supply scenarios.

The study was done using energyPRO, which is a techno-economic energy and mass balance energy system analysis tool designed for simulating and optimizing energy supply systems. In this study, hourly simulations over the course of a year were performed to model the supply of DH under various setups, including configurations with heat storage solutions. The tool prioritized cost reduction in DH supply, activating the most economical solutions first.

The case study focuses on the town of Ozalj in Croatia, where it is assumed that 20 GWh/year of excess heat can be recovered from local manufacturing processes. The town's total DH demand is estimated to be 69.4 GWh/year. Six distinct supply scenarios are examined, all of which include a fixed capacity of natural gas-fired combined heat and power (CHP) plants and boilers. These scenarios differ in their inclusion of additional technologies such as solar thermal systems with seasonal heat storage, the use of excess heat, thermal storage for excess heat, and large-scale heat pumps. Sensitivity analyses are

conducted to evaluate the impact of varying excess heat temperatures and DH supply temperatures on the costs and utilization of excess heat.

The study reveals that it is possible to utilize between 53% and 85% of the available 20 GWh/year excess heat, depending on the specific combination of supply technologies in each scenario. Complete utilization of excess heat is not feasible due to temporal mismatches between excess heat availability and DH demand. However, integrating heat storage for excess heat significantly enhances its utilization.

The modelling also indicates that the inclusion of solar thermal systems, which are prioritized over excess heat, can reduce the utilization of excess heat. Furthermore, lower temperatures of excess heat and higher DH supply temperatures are diminishing the cost competitiveness of excess heat, favouring alternative supply solutions.

3.3.3.3 LOCAL HOURLY ANALYSES OF THE DISTRICT HEATING SUPPLY WITH GRID RESTRICTIONS

In a study by Wittenburg et al. (2023) different pathways for transitioning urban heat supply systems are explored using a detailed full-physical simulation model, with a focus on achieving near-total climate neutrality in the DH system.

The study utilizes a full-physical simulation model developed in Modelica software, an equation-based, object-oriented modeling language suited for dynamic, cyber-physical systems. The model incorporates the main pipes of the existing DH grid, accounting for parameters such as mass flow and pressure. It also integrates the spatial distribution of heat supply technologies and heat demands within the grid. Heat supply operations follow a predefined priority list, which includes options for storing produced heat. Simulations are conducted with hourly resolution, modeling each scenario for a full year.

The study uses Rostock in Germany, as a case study. It leverages potential DH sources identified by the City of Rostock and the DH operator SWRAG. The supply options encompass various technologies, including heat pumps connected to low-grade temperature sources such as rivers, biomass boilers, and gas-fired CHP units. Excess heat sources include heat pumps using sewage, as well as excess heat from electrolysis and industrial processes. The operational priority sequence gives precedence to waste and sewage sludge incineration, biomass heating, and excess heat from industries and electrolysis. This is followed by heat pumps connected to low-grade sources like sewage, rivers, or the sea, with electric boilers and gas-fired units activated last.

Five supply scenarios are investigated, all of which meet a target of 98% climate neutrality for the DH supply by 2035. The study shows that the utilization of excess heat is primarily constrained by heat demand during the summer months, which depends on the installed capacity of excess heat sources. However, heat storage systems are significantly improving the utilization of excess heat. These findings highlight the importance of storage solutions in maximizing the efficiency of low-carbon DH systems.

3.3.4 SECTOR-COUPLED ENERGY SYSTEM METHODS

Unlike the DH-focused energy system approaches discussed in the previous section, this section highlights studies that adopt a sector-coupled energy system approach. This broader perspective goes beyond DH and the heating sector, also including electricity, transport, and industry, while considering the interactions between DH systems and these sectors.

Various energy system models have been used in literature to investigate the utilization of excess heat in DH systems and the surrounding energy systems, e.g., EnergyPLAN (Sorknæs et al. 2022; 2020), Balmorel (Jerez Monsalve, Bergaentzlé, and Keles 2023), TIMES (Sandvall and Karlsson 2023). The energy system models can be applied stand alone or in combination with other approaches mentioned in this report earlier, i.e., GIS, statistics or others. Depending on the purpose of the studies, the existing work has been conducted to investigate the role and potential of excess heat for strategic heat planning in the context of overall energy system in different geographical levels, including municipal, regional and national, and the evaluation of the specific types of excess heat sources, such as datacentres (Jerez Monsalves, Bergaentzlé, and Keles 2023; Sorknæs et al. 2022) and industries (Yuan et al. 2021; Sorknæs et al. 2020).

It was also found that sector-coupled energy system approaches for accessing excess heat potential are still relatively new in literature. Currently, only studies from relative few countries (primarily Denmark) have been published.

3.3.4.1 SIMULATION MODEL-BASED ENERGY SYSTEM ANALYSIS FOR EXCESS HEAT INTEGRATION

A simulation model-based approach is the study by Sorknæs et al. (2022). This study evaluates the benefits of transitioning to 4th-generation DH from the 3rd generation on the national energy system of Denmark in 2045, when the country targets achieving a climate-neutral society. Particularly, the integration of excess heat from industries, PtX plants, and energy efficient datacentres. The work is based on Heat Plan Denmark 2021 (Mathiesen et al. 2021), which aims to investigate on how the heating sector can be interact with the other future energy systems, including heat saving, electrification, energy storage, PtX and e-fuel, data centres, and geothermal.

The GIS analyses are combined with an energy system simulation model to provide inputs for the energy system analyses. The steps for carrying out the study are as follows:

1. **Step 1**: GIS analysis for identifying heat demand and resources

A GIS-based approach is first adopted to identify building-level heat demand, potential energy efficiency measures for heat savings in buildings, opportunities for DH grid expansion, geothermal heat potential, and the availability of industrial excess heat. Excess heat is considered from three sources: existing industries, PtX facilities, and data centres.

Excess heat from existing industries is mapped using business registry data and categorized by temperature ranges, which determine the need for heat pumps under different generations of DH systems. PtX facilities and data centres are expected to grow in the future, with assumptions made about their excess heat potential and integration into DH systems.

2. **Step 2**: Energy system simulation based on EnergyPLAN tool

A simulation-based energy system analysis is conducted to estimate the techno-economic impacts of transitioning from 3rd generation DH to 4th generation DH in the national energy system. This includes evaluating different cooling solutions for data centres.

Denmark's national energy system is simulated on an hourly basis over a leap year using the EnergyPLAN tool (Lund et al. 2021). EnergyPLAN is a freeware software that models energy demand across all sectors—electricity, heating and cooling, transportation, and industry—along with corresponding energy production, conversion, and storage technologies. The heating sector in EnergyPLAN includes both DH systems (centralized and decentralized) and individual heating for households.

The excess heat potential identified in Step 1, together with the heating demand and renewable heat potential, are incorporated into the DH systems in EnergyPLAN. DH systems are designed to support the overall transition to the carbon-neutral national energy system. It is assumed that excess heat from data centres can be used directly in 4th generation DH without the need for heat pumps, using direct water-cooling systems built into the data centres to achieve an output temperature of 60°C for DH. The effects of air cooling are also evaluated for comparison.

Results show that using direct water-cooling instead of air cooling reduces energy system costs by approximately 1.7–1.9 million EUR per TWh of heating delivered to end-users.

3.3.4.2 OPTIMIZATION MODEL-BASED ENERGY SYSTEM ANALYSIS FOR EXCESS HEAT INTEGRATION

Different from the simulation model-based approach, the optimization model-based approach often aims to optimize system configuration. There are two optimization model-based studies focusing on the excess heat recovery from data centres in Denmark, using the Barmorel model (Jerez Monsalves, Bergaentzlé, and Keles 2023) and TIMES model (Petrović et al. 2020), respectively.

Here, a recent study by Jerez Monsalves, Bergaentzlé, and Keles (2023) using Barmorel model is introduced. This study examines the economic and environmental advantages of utilizing cooling flexibility and excess heat from data centres within an energy system that features substantial data centre loads, a high share of variable renewable energy sources, and well-established DH networks. The national energy system of Denmark until 2035 is investigated. Table 2 below shows the objective, sectorial, temporal, and spatial coverage of the Balmorel model developed in this study.

Table 2: Overview of the model coverage in the study (Jerez Monsalves, Bergaentzlé, and Keles 2023)

Objective	Sectorial coverage	Temporal coverage	Spatial coverage
Minimizing total system costs including Investment decisions and operational scheduling of generation and transmission assets.	Electricity, Heating, Hydrogen, data centres	Independently and consecutively optimize every year from 2023 to 2035. Each year includes 192 timesteps, i.e., eight 3-h timesteps per day, three days per week, and eight representative weeks.	Denmark, Norway, Sweden, Germany

Balmorel is a cost-optimization model for analysing large-scale energy systems based on deterministic partial-equilibrium principles, which originally cover electricity and heating sectors. In this study, an extension module representing the cooling system in the data centres is developed, which allows the joint optimization of the data centre alongside the broader energy system. The module includes free cooling, electric chillers, heat pumps, and cooling storage. The demands of electricity and cooling are exogenous at each location and timestep, which are based on the prediction by the Danish Energy Agency. An assumption of 12 km is made for the DH transmission pipe from the data centre to the DH network. The model also assumes that the cooling load is equivalent to the electricity consumption of the IT hardware since all electricity used is ultimately converted into excess heat that should be removed.

Different scenarios on the integration of flexible cooling and excess heat are analysed. Results show that the integration of excess heat recovery can reduce the placement of other power-to-heat technologies, which leads to a 0.8% decrease in CO_2 emission and a 1.7% cost saving. The operational synergies with free cooling can enhance excess heat utilization by 50%.

3.3.4.3 HYBRID APPROACHES ON ENERGY SYSTEM ANALYSIS FOR EXCESS HEAT INTEGRATION

Two examples on hybrid approach are illustrated in this chapter, which both adopts simulation and optimization methods, however, with different principles and purpose.

The **first study** by Eslami et al. (2023), proposes a hybrid approach for optimizing DH system planning in Gaziantep Province, Turkey, for the year of 2030, in which excess heat is included as one of the resources in the overall strategy. The interaction between DH systems and electricity systems is considered. This study employs a multi-layered methodological framework that integrates spatial analysis, an energy system simulation tool, and an energy system optimization model. Within this

framework, the optimization model provides investment insights for renewable energy sources, while the simulation model offers complementary information regarding environmental impacts. The method is as follows:

1. **Step 1**: Special assessment of DH and renewable energy potential

A combination of ArcGIS, the Analytic Hierarchy Process (AHP), Fuzzy Logic, and Boolean Logic is employed to assess the potential of solar energy, wind energy, excess heat, and heat demand density in the Gaziantep region. The Support Vector Machine (SVM) method is used to forecast residential heat demand from 2020 to 2030.

A total of 14 criteria has been included to evaluate wind and solar potential. The excess heat sources considered in this study include a cement plant, a biogas power plant, and a thermal power plant.

2. **Step 2**: Energy system modelling based on hybrid approach

The energy system is modelled in two different ways, i.e., an environmental approach and an economic approach. In the environmental approach, a mixed integer linear programming (MILP) model is created for optimizing renewable energy investment considering the CO_2 emission constraints, and then different system configurations are simulated in EnergyPLAN. In the economical approach, the different energy system configurations are modelled in HOMER software to compare the corresponding LCOE. Based on both environmental and economic aspects, the optimal construction of renewable energy is identified to supply regional DH networks.

The **second study**, conducted by Yuan et al. (2021), explores the trade-off problem between utilizing industrial excess heat and deploying large-scale heat pumps within the DH system, with a focus on maximizing benefits for the overall energy system. The strategic heat planning of the 2050 Aalborg municipality in Denmark serves as case study. A simulation-based optimization approach is employed in this study.

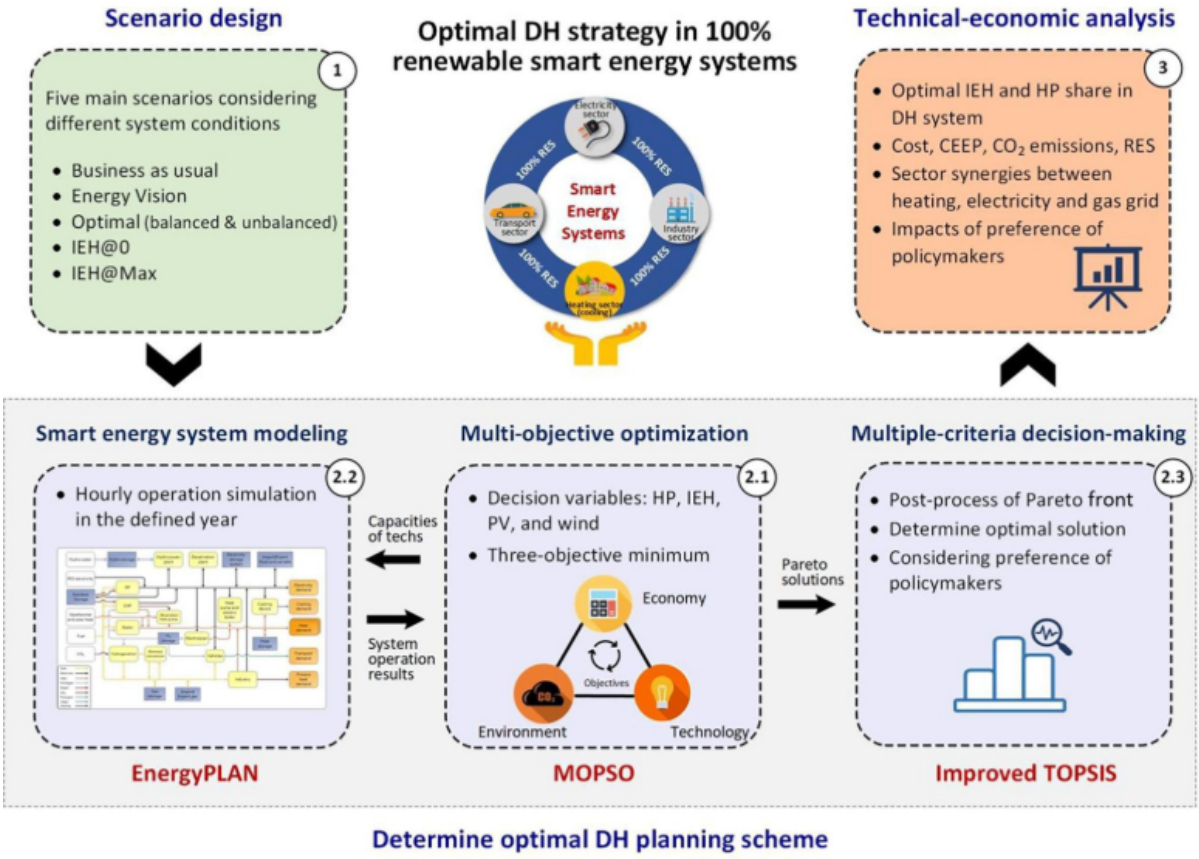


Figure 9: Methodology framework of the study by Yuan et al. (2021). Note: IEH represents industrial excess heat, HP denotes heat pumps, CEEP denotes critical excess electricity production, and RES represents renewable energy sources.

Figure 9 shows the overall methodology framework of the second study (Yuan et al. 2021). The system configuration in terms of the choice between heat pumps and industrial excess heat, as well as renewable electricity generation, is optimized. A multi-objective optimization, using the particle swarm optimization (MOPSO) algorithm, is coupled with the energy system simulation model EnergyPLAN to identify a series of Pareto solutions to balancing the total system cost, CO_2 emission and critical excess electricity production. And then a multiple-criteria decision making method based on the improved TOPSIS model is implemented to post process the Pareto front for identifying the optimal solution.

The technical potential of the local industrial excess heat sources, including cement plants, food production, wastewater treatment plants, supermarkets, and other industries in commercial harbours, are considered as constraints of the model. The results indicate that, while industrial excess heat could technically supply up to 52% of the total DH demand, a 40% share (combined with an appropriate mix of heat pump and industrial excess heat) yields greater overall benefits for the Aalborg energy system.

3.3.5 INTERVIEW AND SURVEY-BASED METHODS

Not all studies are solely relying on quantitative data, such as statistics and measurements. Many also incorporate qualitative data, often gathered through interviews with industry experts or representatives from local manufacturing industries. Such a qualitative approach can be used both as a primary method for estimating excess heat potentials or as complementary to more quantitative techniques, such as those introduced in the previous sections.

Qualitative methods, and perhaps in particular interview-based methods, are most suited for studies with a limited scope, whether that is defined geographically (e.g., a specific region or city) or in terms of the type of excess heat source examined (e.g., originating from specific industrial processes or sub-sectors). Some studies also employ surveys to estimate excess heat potential. While effective in targeted areas or sectors, surveys can be challenging to implement when attempting to assess all excess heat sources across an entire country.

Both interviews and surveys are also commonly used to validate quantitative assessments of excess heat. For instance, estimates derived from national databases can be cross-checked against insights provided by local experts, helping to confirm or refine the accuracy of the data. This triangulation of methods enhances the reliability of the findings by incorporating context-specific knowledge that may not be captured in large-scale datasets.

Moreover, qualitative validation can reveal discrepancies or overlooked factors in national-level assessments, such as operational constraints, seasonal variations, or recent changes in industrial activity. By integrating local perspectives, researchers can better account for real-world conditions and improve the robustness of their models. This approach is particularly valuable in dynamic or under-documented sectors, where quantitative data alone may be insufficient for accurate estimation.

3.3.5.1 EXPERT INTERVIEWS WITH LOCAL MANUFACTURING INDUSTRIES

Moser et al. (2018) present a method for evaluating industrial excess heat potentials and seasonal heat storage integration in DH systems using a socioeconomic approach, based on a case study in Linz, Austria. The study largely relies on interviews with key local industrial stakeholders for estimating the excess heat potentials, combined with technical, economic and macroeconomic analyses to assess the feasibility of seasonal heat storages for industrial excess heat integration. The main steps of the interdisciplinary research method applied are outlined below:

1. Excess heat potential estimation from interviews

Potential industrial excess heat suppliers were identified through company database analysis and consultation with local industry representatives. Interviews were then conducted with five key industrial stakeholders (from steel, chemical, paper, food, and foundry industries) to assess their available excess heat potentials, seasonal variations, and technical constraints. The interviews provided estimates on feasible excess heat potentials while excluding sources deemed economically or technically unviable,

such as low-temperature excess heat that would require costly upgrades (e.g., additional heat pumps). Based on these interviews, a conservative excess heat potential of 40 MW in winter and 55 MW in summer was estimated.

2. DH integration

A case study of Linz DH system was analysed to observe the expected operation of a simulated DH system consisting of thermal boilers, CHP, a heat pump, excess heat integration, and thermal storage in the form of a traditional tank storage and a proposed 80 GWh seasonal heat storage. The system would allow shifting excess heat from summer to winter months while also optimizing CHP dispatch and thereby evaluate the integration potential.

The system operation is modelled based on a relatively simple principle of storing excess heat when energy prices are low and discharging heating when expensive peak-load generation can be replaced.

3. Economic and organizational analysis

An economic cost benefit analysis is conducted, considering a total estimated investment for the seasonal heat storage system, including land acquisition, construction, and equipment, of 106.5 million EUR. Using a heat merit order model, the system is projected to generate 9.6 million EUR in annual revenues, primarily from reduced reliance on fossil-fuel-based heating.

Interviews also highlighted the need for long-term contractual agreements between industrial excess heat providers and the DH operator. Concerns such as potential industry relocations, process modifications, and financial risks were identified as key barriers to implementation.

The authors find that seasonal heat storage combined with excess heat and CHP production would reduce Austria's reliance on imported fossil fuels, improving energy security and reducing CO_2 emissions. However, economic viability was found to be highly sensitive to changes in electricity, gas, and CO_2 prices, making long-term financial stability uncertain. The authors conclude that seasonal heat storage is only economically viable if combined with CHP dispatch optimization. Using the storage purely for shifting summer heat is not financially feasible. Interviews with industrial stakeholders proved essential in refining realistic excess heat estimates and identifying economic and organizational challenges that influence feasibility.

3.3.5.2 SURVEY AND EXPERT INTERVIEWS FOR INDUSTRIAL EXCESS HEAT

This section presents a method by Moser and Lassacher (2020) to identify, categorize, and analyse external industrial excess heat potentials and utilization in Austria. A survey-based approach was employed to gather data on existing external industrial excess heat utilization cases. Main steps of the method are outlined below:

1. Survey design and distribution

A structured questionnaire was designed to collect detailed information on existing implementations, covering technical, economic, and organizational aspects. The survey was distributed to industrial companies, DH operators, and stakeholders involved in excess heat projects. Respondents provided insights on excess heat sources, temperature levels, business models, pricing mechanisms, and contractual structures.

2. Data validation and expert consultation

To supplement the survey responses, data was cross-checked against environmental funding agency records, literature reviews, and expert interviews. Nine Austrian experts from research institutions, industries, and DH companies were consulted to validate responses and identify additional cases not captured through the survey alone.

3. Categorization and GIS mapping

Implementations were categorized based on heat source type (process heat recovery vs. industrial combustion) and end-use application (DH vs. industrial processes). The locations of identified projects were mapped using GIS software to assess regional distribution patterns.

In total, 45 external excess heat reuse projects were identified, with a total installed capacity of 600 MW, delivering 1.75 TWh/year. The authors find that the number of implementations has significantly increased since 2010, reflecting growing awareness and improved techno-economic feasibility. Moser and Lassacher further concluded that DH networks play a crucial role in excess heat integration as they offer long-term stability, reducing investment risks compared to industrial-to-industrial heat exchanges.

The data collected in the survey for this study by Moser and Lassacher was later used in a follow-up study by the same main author (Moser and Jauschnik 2023). This subsequent research expanded the analysis by investigating how projects were initiated, how business models were structured, and what risks were encountered during implementation.

3.3.5.3 SURVEY AND GIS-BASED ESTIMATION OF BIOGAS EXCESS HEAT POTENTIAL

Weinand et al. (2019) presents a method for estimating the technical and economic potential of using excess heat from biogas plants to supply residential heating through DH networks. The study focuses on Germany, which hosts nearly 50% of Europe's total biogas production (currently mostly combusting the gas, in the future probably compressing it; both processes offering excess heat).

The authors apply a survey-based approach combined with a GIS-based spatial analysis to assess heat availability from biogas plants and match it with residential heat demand. The method consists of the following steps:

1. Survey of biogas plant operators

A large-scale survey of around 600 biogas plant operators was conducted to gather primary data on heat utilization, excess heat availability, and plant operation characteristics. The survey included questions on:

- Heat recovery rates and existing utilization pathways (e.g., on-site heating, external supply).
- Barriers to external heat utilization (e.g., infrastructure costs, lack of local demand).
- Willingness to participate in DH networks.

The survey data was validated against government energy databases and expert consultations.

2. Spatial mapping and heat demand matching

The locations of 10,446 biogas plants and 38,414 residential settlement areas were mapped using GIS software. A heuristic matching algorithm was developed to pair biogas plants (heat sources) with nearby settlements (heat sinks) based on a least-cost approach.

DH feasibility was assessed using two key economic criteria:

- CO_2 abatement costs (EUR per ton of CO_2 saved) to evaluate macroeconomic viability,
- and payback period (years) to assess project attractiveness from an investor perspective.

3. Scenario analysis and economic evaluation

Different scenarios were tested to evaluate policy support mechanisms (e.g., CHP production subsidies and alternative heat dispatch strategies. The impact of changing excess heat profiles (e.g., seasonal variations in heat availability) on feasibility was assessed.

The authors conclude that 40% of heat generated in biogas plants remains unused, but if utilized could reduce Germany's CO_2 emissions by 2.5 $MtCO_2$ per year, covering 12% of total residential heating demand in the most viable municipalities. The use of surveys was, according to the authors, essential in uncovering barriers to implementation and to validate excess heat estimates.

3.4 COMPARISON OF PRACTICAL METHODS

Authors: Marco Cozzini, Giovanni dalle Nogare, and Rosanna Paradiso. EURAC

As seen in the previous sections, excess heat mapping can rely on different methods. The problem of estimating excess heat for different industrial activities and commercial sectors was indeed tackled in the literature exploiting slightly different approaches and different data sources. Often, "proxy" estimates are used. In practice, since getting information on excess heat for a specific company is quite time-consuming, general correlations between excess heat and more accessible variables (like the industry

sector and the company size) are obtained from specific surveys and dedicated studies. These correlations are used to estimate excess heat on a large scale. However, on the one hand, specific surveys are usually related to a limited number of cases (small statistical sample), while on the other hand, even within the same industrial sector, a non-negligible variability can occur (factory specific cooling solutions). As a result, an issue of "uncertainty" about the resulting estimates arises. The purpose of this section is to offer some insight on these differences by comparing two excess heat estimation databases based on similar methods, one developed by Aalborg University, and one developed by the Austrian Institute of Technology (AIT). Two sources are used: the MEMPHIS2.0 IEA-DHC project and the LIFE4HeatRecovery project (see below for specific references). While the LIFE4HeatRecovery project also includes urban excess heat (e.g., from supermarkets, as better explained below), the comparison will be carried out on industrial excess heat only.

As already mentioned in previous sections, besides the available excess heat estimation, other issues have to be considered before assessing its actual usage potential into district heating, such as the possibility of local self-consumption or the temporal mismatch between availability and demand. Moreover, the long-term potential might be affected by future changes in industrial processes, where higher energy efficiency might be achieved.

Within the LIFE4HeatRecovery project, excess heat maps for three different demo cases were developed (Dalle Nogare and Cozzini 2023). The methodology includes two different categories: *industrial excess heat* (i.e., excess heat from common industries) and *urban excess heat* (i.e., excess heat from commercial/service activities, e.g., refrigeration in supermarkets, hospital, ice rinks, etc.). Both excess heat categories were joined in common maps through a properly developed QGIS plugin.

For *industrial excess heat* sources, the available energy was calculated based on simple proxy data, namely the Statistical Classification of Economic Activities in the European Community code, commonly referred to as NACE and identifying the industrial sector, and the number of employees (yielding an indication of the company size). Excess heat was estimated through conversion coefficients taken from two different literature sources (see below). To map a given city area, company data have been retrieved first. This was done through proper operators (e.g., the local chamber of commerce). The company address was then used to geo-reference the heat sources in a GIS system, through common automatic tools (some manual consistency checks were also carried out, as typos or other issues in addresses are relatively common). Finally, the excess heat was calculated through the database of coefficients classified by NACE code and number of employees.

For *urban excess heat* sources, the available energy was instead typically estimated resorting to values per unit area (retrieved from literature) scaled on the activity size. In this case, the process was fully automated. The available tagging in online databases (e.g., Google services) was used to identify activities belonging to a predefined list; then the corresponding building was identified in GIS, and the related floor area was retrieved. Finally, excess heat was calculated by multiplying the specific excess heat value by the area size. For selected activities, alternative solutions were implemented (e.g., for the

case of ice rinks, where the size of the rink field is typically standardised, literature data related to specific cases were used, avoiding the use of building area data).

Focusing on the case of industrial excess heat, the LIFE4HeatRecovery project (coordinated by EURAC and involving Aalborg University as a partner) tried to tackle the issue of *uncertainty* in available data. This was initially built on the experience gained in the MEMPHIS 2.0 project (Pelda et al. 2023), where excess heat conversion coefficients previously estimated by AIT (Loibl 2017) for a limited number of industrial sectors were validated for a few cases. In MEMPHIS 2.0, out of 4 validation cases in different industrial sectors, 3 cases showed that the excess heat assessed through direct contacts with the companies was found to be in line with estimates (at order of magnitude level), while for 1 case a factor 10 of difference was found (for the dairy sector, where the recovery coefficient possibly neglected low-temperature excess heat). In LIFE4HeatRecovery, the Austrian excess heat estimation coefficients were then compared with similar but independent estimates based on Danish statistics. Original Danish data came from Huang, Bühler, and Holm (2015). Danish data were available for a much larger number of industrial sectors, significantly enlarging the scope of the method. The comparison between Austrian and Danish data was carried out both for single NACE codes and at city level for two of the demo cases considered in the project: Aalborg in Denmark and Ospitaletto in Italy. For the third demo case, Heerlen in the Netherlands, company data collection was hindered by more restrictive privacy laws.

For the case of single NACE coefficients (including bakeries, breweries, chemical factories, dairies, foundries, manufacturing of vehicles, manufacturing of plastics, and printing), significant differences were found between the two coefficients datasets. The maximum difference between the two estimates was found to be up to a factor of 10 (for the case of dairies, where the Danish coefficient was higher). Moreover, in some cases one data set was found to provide higher estimates than the other, in other cases the opposite, depending on the industrial sector. This is roughly in line with the validation process carried out in MEMPHIS2.0 and described above. It seems to confirm that in general the correct order of magnitude can be captured, but that significant deviations (even up to a factor of 10) might occur. Multiple uncertainties can contribute, e.g., the use of employee ranges rather than precise values, different classifications of temperatures ranges, and unclarities in industrial sector selection (for some large factories, multiple NACE codes apply).

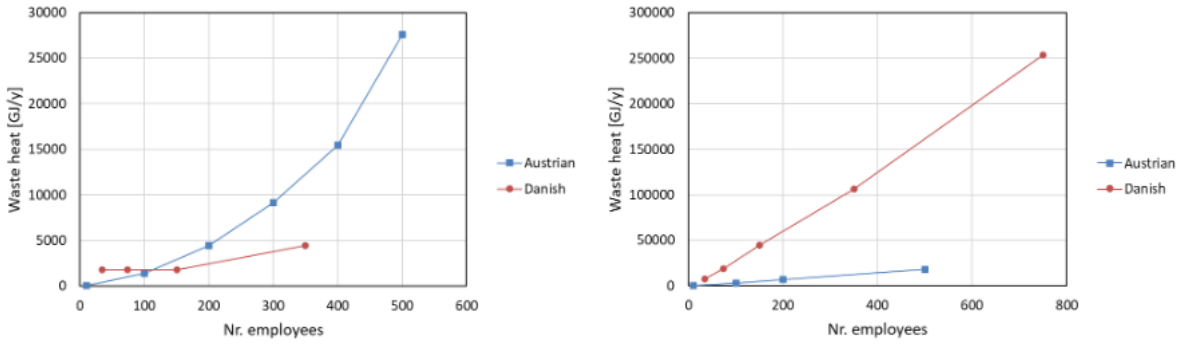


Figure 10: Comparison between Austrian and Danish waste (excess) heat coefficients for two sample cases. Left panel: bakeries (NACE 10.70). Right panel: dairies (NACE 10.50). Overall excess heat is represented, combining different temperature ranges.

For *Aalborg*, the great majority of the mapped activities did not have a corresponding excess heat coefficient in the Austrian database. Only for about 10 activities could a joint estimate be made, see Figure 10. As a result, the estimate based on the Danish coefficients results about *6 times higher* than the one based on Austrian coefficients.

For *Ospitaletto*, seven industrial excess heat cases were mapped. All of them belonged to industrial sectors where both Austrian and Danish conversion coefficients were available, but after further screening the comparison was restricted to five companies. In this case, an almost opposite result was found, with the estimate based on the Danish coefficients resulting about four *times smaller* than the one based on the Austrian ones.

The comparison at city levels reflects well the discrepancies observed at the level of single NACE codes. As already commented, while the orders of magnitude of the estimates are mostly in agreement, significant uncertainty exists. This is not surprising, due to the approximate statistical nature of the underlying methodologies.

3.5 SUMMARY AND CONCLUSIONS OF CHAPTER 3

The review shows that research on district heating and methods for identifying the excess heat potential are increasing in scientific literature, and a wide variety of methods have been applied. The methods applied are typically chosen based on data availability for the study.

Research on excess heat for district heating has grown significantly, particularly after 2015. Most studies originate from Europe and China. Historically, industrial processes have been the primary focus of excess heat studies. In recent years, attention has expanded to include data centres, wastewater and sewage systems, and, more recently, Power-to-X technologies.

Analyses have been conducted at various geographical scales, ranging from individual projects and cities to regional, national, and European-wide studies. Most of the research focuses on city and project levels, followed by national and regional assessments.

Five main categories of methods were identified: statistical methods, spatial mapping methods (GIS), energy system analyses, qualitative methods, and hybrid approaches. Each category offers distinct advantages depending on data availability, geographical scope, and analysis objectives.

The most applied methods are energy system analyses, which examine temporal integration of excess heat into district heating systems. GIS-based mapping methods are widely used to identify spatial relationships between heat sources and district heating networks. Statistical approaches rely on emission and energy consumption data, while qualitative methods such as interviews and surveys provide local validation and context. Hybrid approaches that combine GIS, simulation, and optimization are increasingly favoured for strategic planning.

Insights from the review indicate that there is no universally best method; the choice depends on context. Integration challenges include economic feasibility, temperature levels, and stakeholder cooperation. Proxy-based estimation methods can vary by a factor of ten, underscoring the need for validation. A clear trend toward combining GIS and energy system modelling is evident, as these approaches provide comprehensive spatial and temporal insights.

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4. INDUSTRIAL INTEGRATION

Authors: Thomas Kohne (TUD), Oskay Ozen (TUD), Dietmar Schüwer (WI)

Contributors: Stefan Reuter, Nicolas Marx, Wolfgang Gruber-Glatzl, Jasmin Pfleger Marco Cozzini, Giulia Novati, Meng Yuan, Oddgeir Gudmundsson.

This chapter analyses the integration of industrial energy systems (InES) into district heating and cooling (DHC) networks from an industrial perspective. The guiding questions of this chapter are:

- What kind of techno-economic and systemic knowledge from the perspective of InES is crucial for experts, operators, and decision makers to manage the uses of excess heat potential?
- Why is the transformation of thermal energy supply and excess heat sources within InES important for excess heat integration into DHC?
- What are the technical components, boundary conditions, and research approaches for a successful excess heat recovery or delivery of InES?

The chapter is structured as follows:

- Chapter 4.1 describes the characteristics of InES considering multi-modality, cascaded heating and cooling networks, as well as different temperature levels and components with a focus on thermal networks (conversion, transport, and storage). Thus, it gives the necessary context for the following analysis of district heating connections of these InES.
- Chapter 4.2 provides an overview of innovations in new climate-friendly energy sources and energy-efficient converters for supplying industrial process heat in the future. The 4-Step Model outlined provides guidelines for the efficient use of limited renewable energy resources and forms the basis for assessing the expected changes in future excess heat potential in the next chapter.
- In Chapter 4.3, the various influencing factors relevant to process heat are examined, including the deliberate phasing out (“exnovation”) of fossil energy, changes in production volumes, product or process changes, and new applications like Carbon Capture and Storage (CCS). The mechanisms of industrial transformation towards climate neutrality are explained and, finally, their expected impact on future excess heat utilisation is assessed qualitatively.
- Chapter 4.4 summarizes specific framework conditions such as temperature and pressure levels, network hydraulics, success factors, and regulation to design a district heating connection of InES with focus on the heat transfer station. Moreover, it gives an overview of existing techno-economic concepts for complex heat transfer stations and the systemic integration of InES into DHC.

4.1 TECHNO-ECONOMIC ANALYSIS OF INDUSTRIAL ENERGY SYSTEMS

This techno-economic analysis of industrial energy systems is, in large, a translation of chapter 2.2 in Kohne (2023) with the permission of the author, Thomas Kohne.

The term *industry* as part of the economy describes companies that predominantly produce material goods as products and mainly use mechanical equipment for this purpose with extensive division of labour and specialization of employees [Voig08]. In this chapter, the manufacturing industry is addressed, which in turn can be divided into a total of 24 industrial sectors depending on the predominantly manufactured material goods of the companies, including the manufacture of chemical products or mechanical engineering [Euro08, Vere08]. Material and immaterial production factors are used to manufacture these goods at industrial sites and are processed or handled by industrial processes or process chains consisting of manufacturing, processing, procedural, and logistical sub-processes (Figure 11). In addition to operating resources, materials and labour, production factors also include energy [Müll09; Sche14].

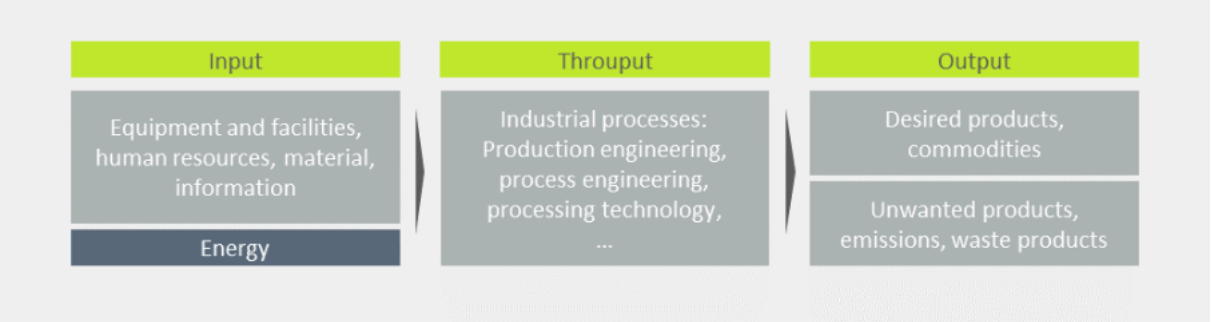


Figure 11: Input, throughput, and output of industrial processes (Kohne 2023).

The energy required to operate the sites of industrial companies is procured and converted in the form of energy services via the energy conversion chain until it is used [Posc11]. In industry, final energy procurement mainly includes electrical energy, fossil fuels such as natural gas, but also district heating or alternative fuels such as hydrogen [Dehl20]. Final energy can be provided from fossil fuels, but also from renewable energy sources, such as solar radiation or ambient heat.

4.1.1 ENERGY USE IN INDUSTRY

The procurement of purchased final energy and the integration of environmental energy as final energy at an industrial site is provided through energy conversion, storage, and distribution in line with demand for energy services as useful energy. Energy services at an industrial site are diverse and can be differentiated as follows [Rudo08; Pant19]:

- Technological processes require energy, e.g., to manufacture products or to convert energy. These processes can be divided into mechanical processes (e.g., for machining or the generation of compressed air), thermal and thermochemical processes using heating and cooling (e.g., for hardening processes or the cooling of lubricants, Fischer-Tropsch synthesis), and electro-technological processes (e.g., for electrolysis or electroplating).
- Room conditioning, i.e., the provision of heating, ventilation, air conditioning, as well as the provision of domestic hot water.
- The transportation of employees and materials at the industrial site requires energy, such as fuel or electrical energy.
- Lighting at the industrial site is necessary for the well-being, performance, and occupational safety of employees and requires corresponding electrical energy.
- Finally, information and communication technology (ICT) requires electrical energy for the processing and storage of data and is becoming increasingly important in the course of digitalization, also in terms of energy requirements.

As can be seen in Figure 12, primary energy (e.g. natural gas) can undergo several conversion steps (e.g., to steam as a form of secondary or final energy) before it is eventually made available as useful energy (e.g., thermal process energy). This allows for energy requirements in technological processes to be differentiated in their applications. For example, some of the energy is required for the industrial company's production processes, such as metalworking processes or process engineering processes. These processes can be very heterogeneous compared to the industrial sectors [Bles17]. Another part is required for cross-sectional technologies. The term *cross-sectional technologies* refers to technologies that are used across different branches of industry and are often assigned to energy conversion, storage, and distribution [Müll09].

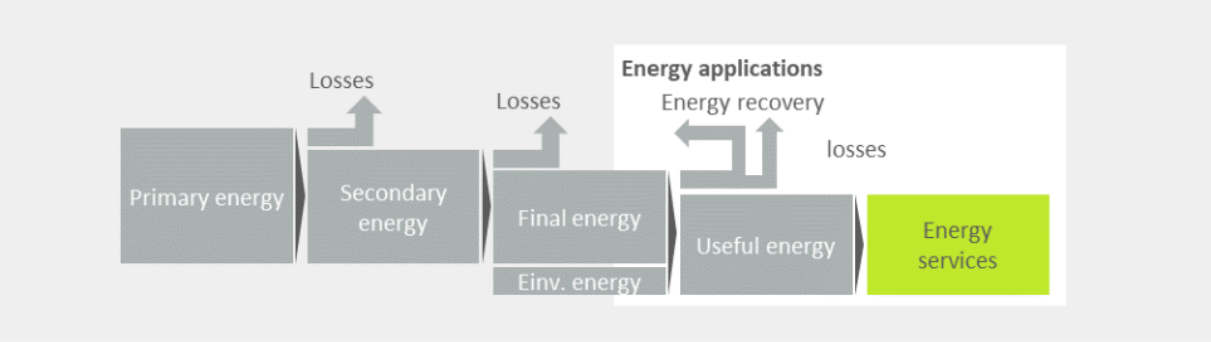


Figure 12: Energy flow from primary to useful energy with corresponding energy losses (Kohne 2023)

In Germany, as an example for an industrialized country, 18% of the total final energy demand was used for industrial process heat in 2023 (AGEB 2025). Including the renewable shares of electricity and district

heating, over 80% of process heat was provided by fossil fuels, see *Figure 13*. Industry therefore faces the major challenge of substituting this demand in just a few decades.

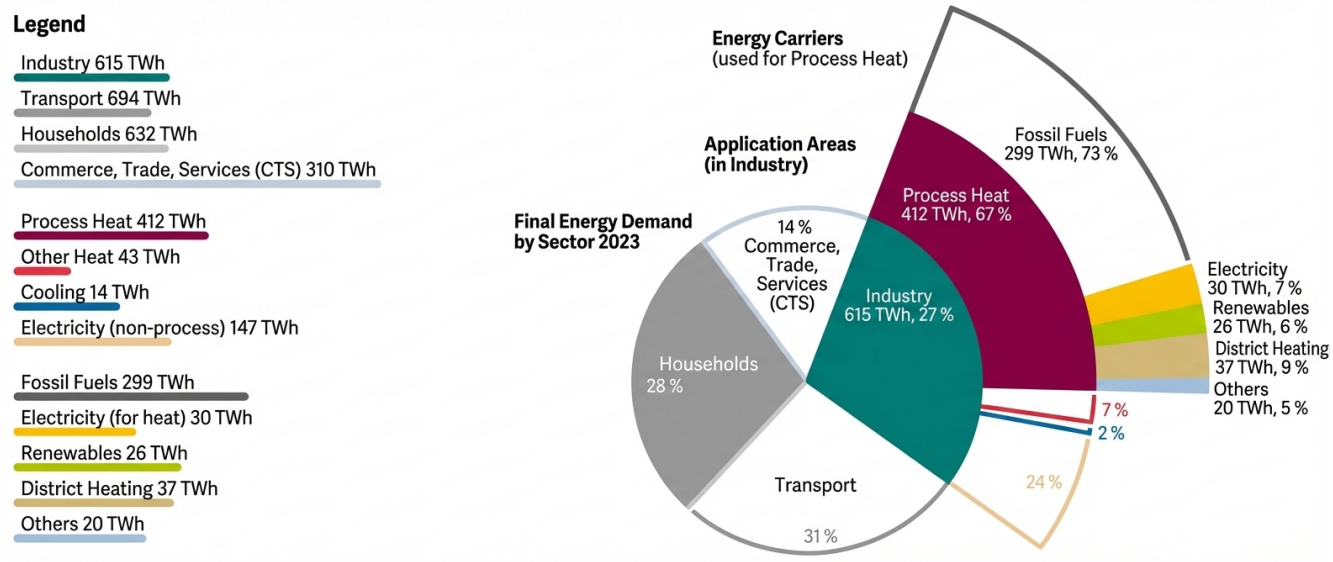


Figure 13: Composition of industrial process heat and share of total final energy demand, Germany
Source: NRW.Energy4Climate 2026, own translation, data from (AGEB 2025)

4.1.2 ENERGY CONVERSION, STORAGE, AND DISTRIBUTION

Cross-sectional technologies are used to provide the energy requirements for energy services at the right time, in the right place, and in the right form of energy. The entirety of these technical systems for energy conversion, storage, and distribution is usually assigned to building technology or technical building equipment (TBE) or supply technology (Figure 14) [VDI4700]. The auxiliary final energy demand for the operation of energy supply technology (i.e., excluding the industrial processes themselves) is estimated to be between 10 and 40% of the total final energy demand, depending on the industry [Rein17].

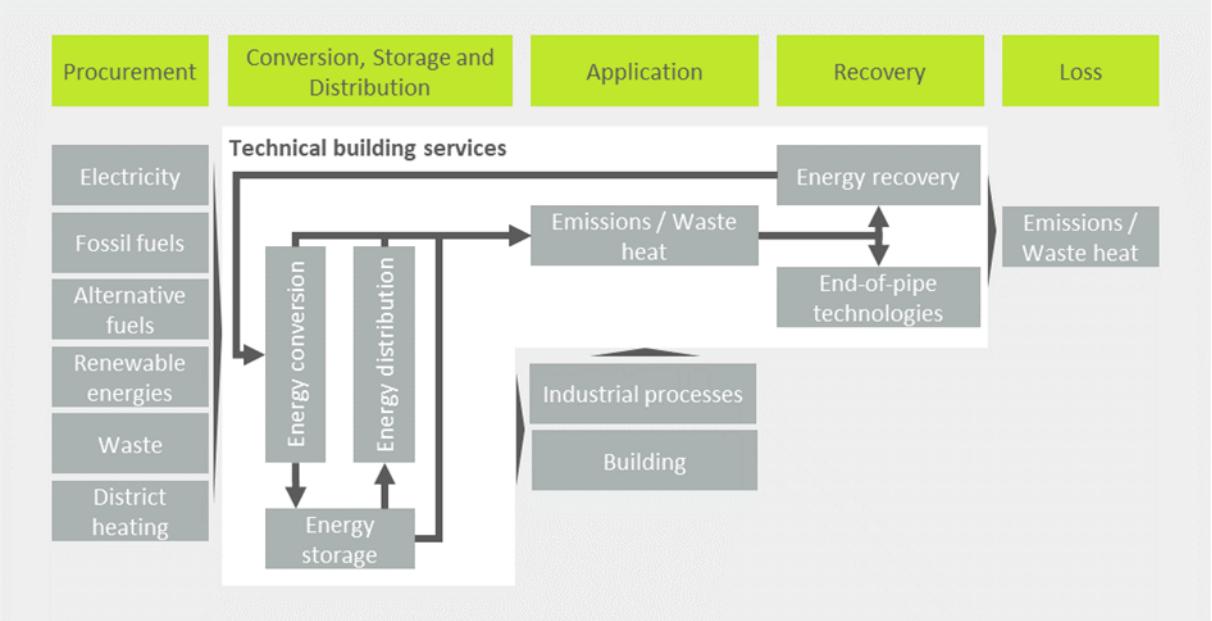


Figure 14: Diagram of energy use in industry (Kohne 2023)

In energy conversion, a distinction is made between centralized and decentralized energy converters [Wohi13]. Central energy converters are installed to cover the energy requirements of several technical systems and processes at the industrial site. Such technical systems can include various heating and cooling systems as well as combined heat and power (CHP) systems, but also technical systems for generating compressed air, for using renewable energies such as photovoltaics (PV) and geothermal energy or ventilation systems [Bles17]. Energy sources such as steam, hot and warm water, cooling and cold water, but also electrical energy, natural gas, or compressed air are used to distribute energy via energy networks at the industrial site [DIN276]. This centrally supplied energy can also be referred to as input energy [Leem92]. The energy networks used to distribute the input energy sources consist of technical systems such as pipelines with pumps and valves or wires with transformers and circuit breakers. Storage technologies such as thermal or electrical storage are used in energy systems to decouple energy generation and conversion from energy demand over time. Thermal energy storage systems can be used passively as buffer storage or actively for greater energy recovery and the integration of renewable energies such as solar thermal energy. Electrical storage technologies, such as batteries, are also used for load flexibilization and for better utilization of electrical energy from intermittent, volatile renewables, e.g., electricity from PV modules [Ster14]. The entirety of the technical systems from central energy conversion, storage, and distribution to the provision of input energy can be referred to as industrial energy systems.

Input energy can ultimately be converted into the corresponding useful energy at the point of use by decentralized energy converters such as motors or systems for heating and cooling circuits within industrial processes. During the operation of energy converters and technological industrial processes, energy is lost, typically in the form of excess heat. By recovering energy, some of this lost energy can

be fed back into the industrial energy system and used elsewhere, which increases the energy efficiency of the overall system. If energy recovery is not possible at the industrial site, this surplus energy can also be made available, for free or for a fee, to an energy supply company, e.g., industrial excess heat or surplus electrical energy [Dehl20]. Energy recovery includes technical systems for the capture of lost energy, e.g., the use of heat exchangers or heat pumps for the recovery of industrial excess heat [Bles17]. A comprehensive overview of technical systems for energy conversion, storage, and distribution as well as for energy recovery can be found in [Hess12; Bles17; Dehl20].

4.1.3 INDUSTRIAL ENERGY SYSTEMS AS A COMPOUND

Industrial energy systems at industrial sites can be considered holistically for planning and operation. By using various energy converters, the cross-domain energy networks, e.g., for electricity, heat, cooling, gas, and compressed air, are coupled together. In addition to the various energy networks and converters, energy storage and recovery systems can also be integrated into planning and operating approaches. With the aim of utilizing synergies between the various subsystems, these networked energy systems are also referred to as multi-modal energy systems [Thie17b; Dole21]. Other terms include integrated [Fuen16], hybrid [Pant19] or intelligent [Lund12] energy systems, and the term energy network system [Sche16].

Figure *15* shows an example of a multimodal industrial energy system using the example of the Energy Efficiency and Application Center (ETA) research factory at the Technical University of Darmstadt (also TU Darmstadt or TUDa) [Abel18] as a function of internal and external influencing factors [Pant19]. In different industry sectors, steam networks can also be integrated for temperature demands above ~150°C, or ammonia networks for cooling purposes below 0°C.

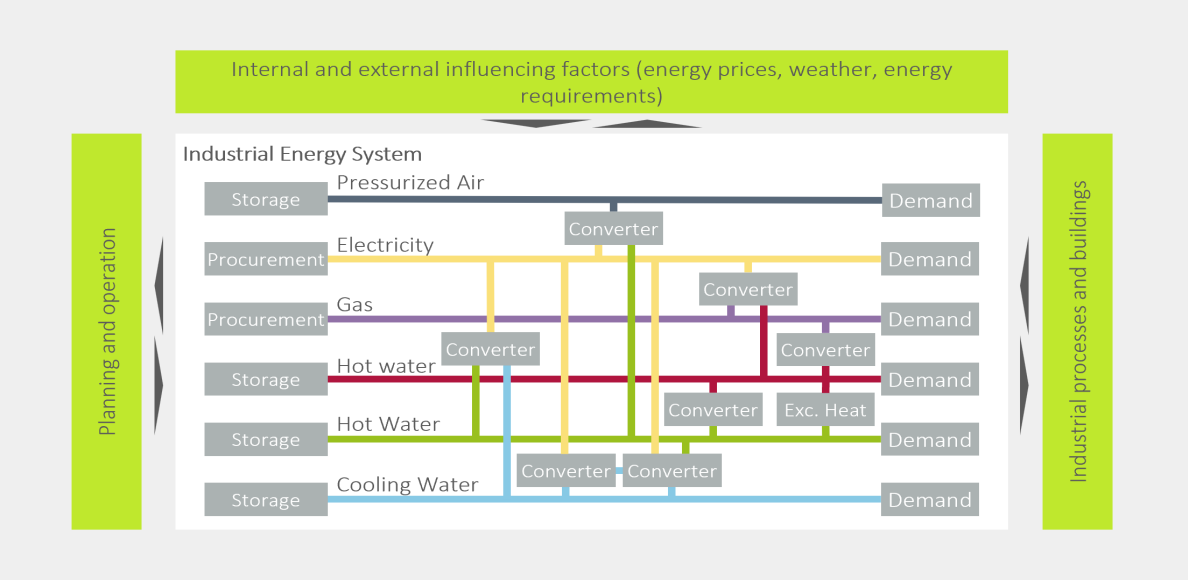


Figure 15: Multi-modal industrial energy system using the example of the ETA Factory at Darmstadt

Technical University, a highly energy efficient large-scale industrial demonstrator for the metalworking industry. "Excess heat" shortened to "Exc. Heat" in the diagram (Kohne 2023).

Multi-modal industrial energy systems are characterized by high dynamics in different energy requirements, e.g. due to changing production schedules and fluctuating outside temperatures [Thie12]. In addition to the energy requirements, the operating behaviour of the technical systems is also dependent on external influences such as the outside temperature [Bles21]. Due to the possibility of energy recovery, e.g., from industrial excess heat, there is also an interaction with industrial process systems and the buildings at the industrial site; for example, excess heat recovery systems are commonly designed with thermal energy storages, which have the purpose of decoupling excess heat recovery from the fluctuating supply of the excess heat source, thus ensuring that production processes are not negatively impacted by the integration of recovery systems [Hirz13]. For the provision of input energy, multi-modal industrial energy systems obtain final energy from central (national or international) energy systems such as the electricity grid, the gas grid, but also from district heating networks. The corresponding price components of the final energy supply must be considered during planning and operation [Matz17a]. The planning of such systems is usually based on procedures for planning building services (e.g., [VDI2067; VDI2073]) and factory planning [VDI5200]; operation usually takes place using rule-based approaches via building automation (BA) within the building management system (BMS) [VDI3814]. Numerous research approaches attempt to improve the planning and operation of these multi-modal industrial energy systems using methods and algorithms such as mathematical optimization, e.g., in [Atab17; Baum20].

4.1.4 THERMAL ENERGY NETWORKS IN INDUSTRY

An elementary subsystem in industrial energy systems is the heating and cooling supply, i.e., the provision of heat (process heat, space heating, hot water) and cooling (air conditioning, process cooling) at industrial sites (see Figure 13: Composition of industrial process heat and share of total final energy demand, Germany Source: NRW.Energy4Climate 2026, own translation, data from (AGEB 2025)). To provide heating and cooling as input energy, thermal energy networks are used at industrial sites, in which the corresponding energy is provided via an energy carrier medium, usually steam or water [Hess12]. This medium is transported from the heat generators to the heat consumers (flow), and from the heat consumers back to the heat generators (return flow) via pipes and by means of pumps and valves (Figure 16) [VDI2073]. Heat generators and heat demands can be integrated in a series or parallel connection (the figure shows heat generators in series and the demand side in parallel). The various connection options and their characteristics are explained in more detail in [VDI2073]. To supply heat, it is extracted from the medium by lowering the temperature between the flow and return by means of direct or indirect heat exchange. Further heat can be released from the medium via a phase change at a constant temperature level, e.g., from steam to water as an enthalpy of vaporization [Böge14]. In the cooling supply, the excess heat energy to be dissipated from the cooling requirements is transferred to the medium, thus raising the return temperature compared to the supply temperature. The cooling

generators dissipate this heat from the medium. The heat output can be set with the volume flow and temperature difference between the flow and return [VDI2073].

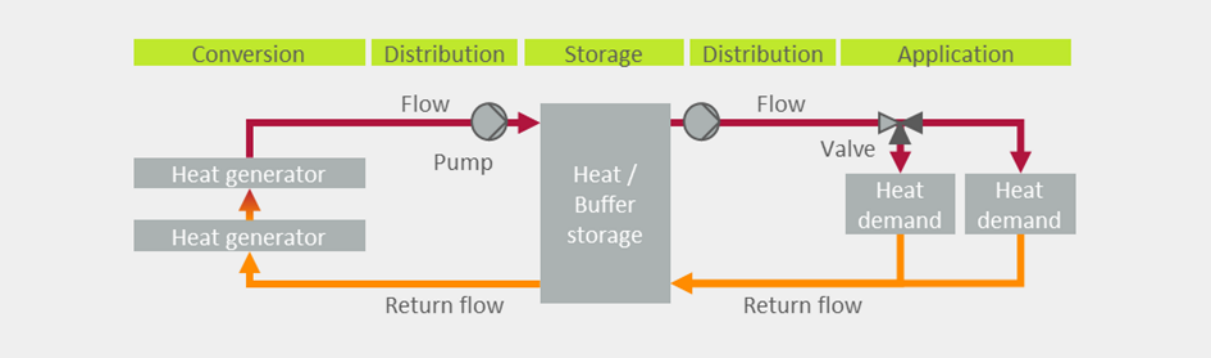


Figure 16: Diagram of thermal energy networks (Kohne 2023).

Heat transfer plays a central role in fluid-based thermal energy systems. Heat exchangers and control valves are often used as technical systems for this purpose. Depending on the requirement of the process, the heat exchanger can be co-current, counter-current or cross-current [Step13]. For simplification purposes, the basic principle will be briefly illustrated using the example of the counter-current heat exchanger (Figure 16): Two fluids with different inlet temperatures and mass flows interact along a heat transfer surface. By the second law of thermodynamics, heat flows from the warmer fluid to the cooler. The transferred thermal energy depends on the initial temperatures and is calculated using the mean temperature difference of the fluids, the heat transfer area A and the heat transfer coefficient [Step13]. Various methods can be used to calculate the transferred thermal power, which map this as a function of the mass flows and input temperatures. One such method is the so-called number of transfer units (NTU) method. For a more detailed explanation of this method, we refer to [Step19].

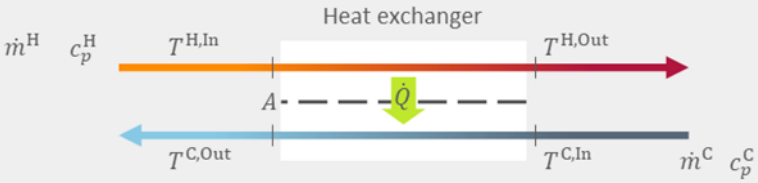


Figure 17: Schematic diagram of a heat exchanger (counterflow heat exchanger). A: heat transfer area, cp: specific heat capacity, ˙ m: mass flow, ˙Q: transferred heat, T: temperatures (Kohne 2023).

In thermal energy systems, the temperature level of the energy networks, but also the requirements of the energy demand for temperatures, are decisive, as the efficiency of energy converters and the usable energy or exergy depend on this [Hess12; Baeh12]. At temperatures over 150°C, steam is typically used. These higher temperature requirements are commonly encountered in the chemical industry, paper production, or partly also in the food industry [Schm04]. Alternatively, the heat is provided directly

in the process via combustion of fossil fuels or electric heaters [Schm04]. There are various applications in cooling supply, such as air conditioning of rooms and buildings or cooling of technical systems such as production machines with temperatures between 0 and 30°C.

Due to the diverse temperature requirements for heating and cooling in industry, several thermal energy networks with different temperature levels, i.e., with different flow and return temperatures, are often operated at industrial sites (Table 3) [Klei19]. These networks can be coupled with each other via technical systems such as heat pumps or heat exchangers (see also thermal energy networks Figure 16) [Dehl20], so that the entirety of coupled thermal energy networks with different temperature levels can also be referred to as cascaded thermal networks in industrial energy systems [Kohn23d]. Various methods, e.g., simulation models or pinch analysis, are used to make the heating and cooling supply at industrial sites more energy-efficient through optimized interconnection and temperature adjustment [Kurl18; Flum21].

Table 3: Temperature levels and energy services of typical cascaded thermal energy systems (Kohne 2023)

Type	**Flow /°C**	**Return flow /°C**	**Energy services**
High to low pressure steam	120-240	80-160	Process heat for chemical processes, hygiene treatment, drying
High temperature water	90-150	70-120	Cleaning processes, machining processes
Medium to low temperature water	50-70	30-50	Space heating, cleaning processes, integration of excess heat, domestic hot water
Cooling	10-30	15-40	Cooling of production machines, cooling of energy converters, air conditioning
Refrigeration	1-6	6-12	Re-cooling in the food industry, air conditioning

4.1.5 INDUSTRIAL EXCESS HEAT

During the energy conversion of final energy and environmental energy, as well as in industrial processes, excess heat is generated in addition to the desired useful energy. Excess heat is thus a by-product, or waste product, of industrial processes [Star20] and can therefore also be referred to as lost exergy. In industry, excess heat is generated in a variety of technical systems such as production plants with compressors, combustion engines, and electric motors, e.g., in combustion and drying systems or systems for utilizing process heat, as well as during heat dissipation via cooling processes from

compressed air, refrigeration, cooling, or air conditioning systems [Dehl20; Hirz13]. Excess heat can be reduced by increasing the energy efficiency of technical systems (avoidable excess heat). From an energy system point of view, unavoidable excess heat offers great potential to reduce primary energy demand, and thus energy costs, and ultimately emissions from final energy demand. Depending on the proximity of a heat powered process to the process in which the excess heat is generated, a distinction is made between four options for utilizing unavoidable excess heat [Grah15]. Unavoidable excess heat refers to the portion of excess heat stemming from processes that cannot be reduced or eliminated through further system optimization, as elaborated later.

The direct re-integration of excess heat into processes and systems (i.e. enabling heat recovery) improves the overall energy efficiency of those processes and systems. Excess heat can also be integrated into other operating processes or systems, reducing the primary energy demand despite transportation losses. In addition, heat can be converted into other forms of useful energy, such as cooling energy or electricity, albeit with conversion losses. Another option is the transfer of excess heat to third parties via district heating networks operated by utilities, where surplus heat from unused heat generators can also be integrated alongside the excess heat. An exemplary prioritization scheme can be found in Figure 18.

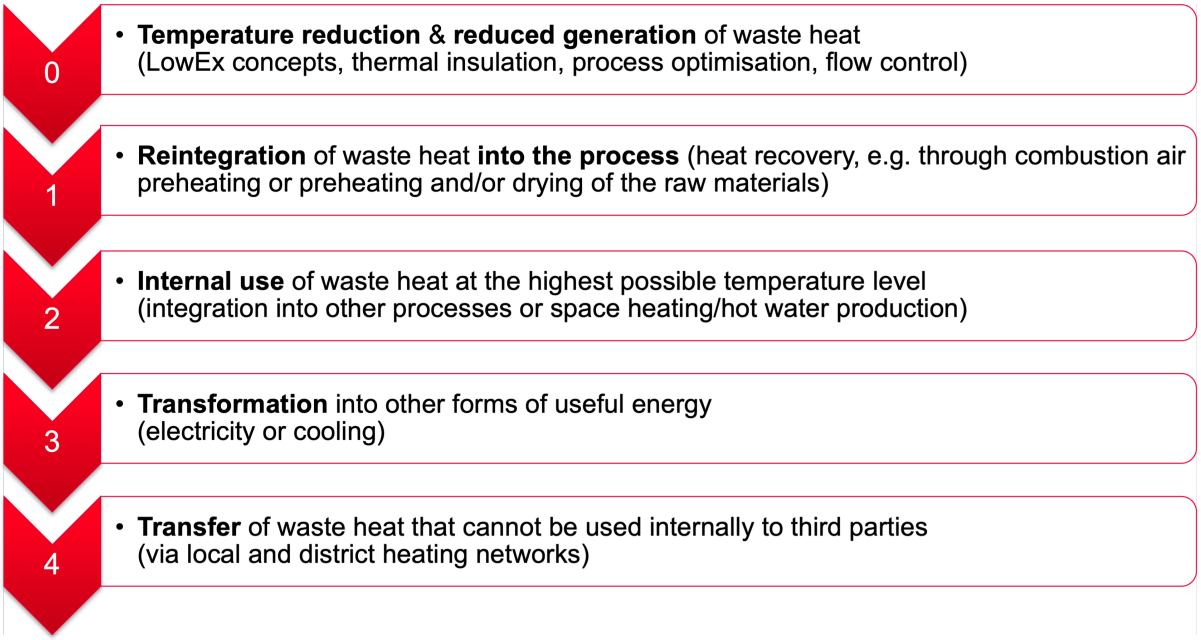


Figure 18: Four steps of (unavoidable) excess heat utilization
Source: own depiction (Wuppertal Institute)

The type of use as well as the technical feasibility, economic viability, and ecological sense of excess heat utilization must be determined by analysing the heat sources and sinks, i.e., the excess heat and

the heat demand. In particular, the available and required energy quantities, but also the excess heat output and required heat output, as well as the time availability and requirements of the heat source and sink, must be considered (Figure 18). The integration of heat storage can support balancing between source and sink availability. Furthermore, the temperature level or temperature range of the heat source and sink can be decisive for cost-effective excess heat utilization. [Dehl20] lists the following exemplary temperature ranges for excess heat:

- 100 - 1000°C: in exhaust gases from combustion and heating processes,
- 100 - 150°C: in steam from steam generation systems,
- 40 - 90°C: in drying systems, compressed air, refrigeration, warm wastewater and cooling water,
- 20 - 40°C: in ventilation systems.

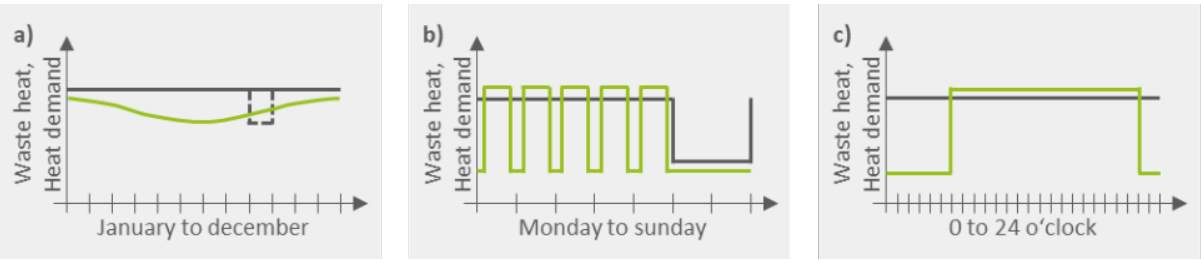


Figure 19: Examples of excess heat (black) and heat requirements (green) over time. a: annual, b: weekly, c: daily. Due to continuous processes and thermal lag of large excess heat sources, availability of industrial excess heat typically exceeds productive working times (i.e., shift operation), as can be seen in b and c (Kohne 2023).

Even if the temperature requirement of the heat demand is higher than the excess heat temperature, excess heat can be a valuable heat source for heat pumps. Finally, the fluids that release, transport, and absorb the excess heat (e.g., supply/exhaust air, exhaust gas, hot/cooling water, wastewater, steam, combustion air) and the local positions of the heat source and sink in relation to each other, must be considered [Dehl20]. In the context of this work, excess heat utilization as a transfer to third parties in the planning of a district heating connection is addressed. The Nenia project [Blöm19] determined that, e.g., in Germany between 20 and 60 TWh of excess heat per year could be utilized. However, economic and ecological feasibility must be examined together with the local energy supply company [Star20].

4.2 TRANSFORMATION OF INDUSTRIAL THERMAL ENERGY SUPPLY

The introduction of this chapter includes translated parts of chapter 2.2 in [Kohn23x] with the permission of the author, Thomas Kohne. Chapters 4.2.1 and 4.2.2 include translated parts of (Schüwer and Holtz, 2023) and (Schüwer et al. 2023) with the permission of the authors Dietmar Schüwer and Georg Holtz.

Against the backdrop of climate change and international climate targets, industrial companies are increasingly setting themselves the goal of becoming climate neutral. In addition to transparency and pricing of emissions, companies have various options for reducing their own emissions (regardless of their source being energy or resource based), which can be divided into three categories [Hann21]:

- **Reduce**: Reduction of energy demand and thus emissions throughout the provision of energy in the energy conversion chain,
- **Substitute**: use of a form of energy with lower emissions in the energy conversion chain (renewable energies),
- **Compensate**: Financing other measures to reduce emissions outside the company (emissions are saved elsewhere).

For the technical description of the transformation of industrial energy systems, measures for reduction and substitution are particularly relevant. The most important measures for the transformation of industrial energy systems can be summarized as follows [Bard22; Bata18; Bata21; Rift20; Wei19]:

- **Increasing energy efficiency**: reducing useful energy demand through more efficient industrial processes, installing more energy-efficient energy converters,
- **Integration of excess heat**: from processes, e.g., from industrial furnaces, from energy converters, e.g., compressors for compressed air, or indirectly via heat pumps from refrigeration networks,
- **Electrification of energy converters**: use of electricity-based technologies such as electric boilers or heat pumps,
- **Renewable heat sources:** heating/cooling from, e.g., geothermal, solar thermal, or ambient sources,
- **Alternative fuels**: purchase of low-emission hydrogen, use of biogas.

The transformation of industrial energy systems, such as the replacement of system components, includes the use of renewable energy sources (photovoltaics, solar thermal energy, geothermal energy) and reduces emissions [Bata18; Bata21]. In addition, a more efficient and flexible use and operation of industrial energy systems can be implemented through the connection of energy networks, e.g., in heating networks via heat exchangers and heat pumps [Abel18; Mohd16]. When planning the district heating connection of industrial energy systems over a long period of time, this potential transformation must be considered, as future excess heat may depend on the transformation [Kohn23c]. Even today,

alternative energy sources and technologies for the provision of process heat are already available or will become soon. Their integration enables a significant reduction in CO_2 emissions, in some cases leading to complete (local) greenhouse gas neutrality.

In the following sections, the transformation of thermal energy supply in the industry will be discussed in more detail. With regards to alternative heat generation options, relevant technologies are analysed according to their technical characteristics as well as their energy and resource efficiency and how they can be used as optimally as possible in the industrial and overall energy system according to these aspects. This analysis in chapter 4.2 serves as a basis for estimating the qualitative changes in industrial excess heat potential in chapter 4.3, which can be expected in the future in light of industrial transformation.

4.2.1 TECHNOLOGICAL OPTIONS FOR CLIMATE-NEUTRAL PROCESS HEAT

Figure 20 shows the technical possibilities for decarbonising industrial process heat generation using renewable heat sources, unavoidable excess heat, renewable electricity, biomass (including biogas), residual materials (e.g. from the paper industry) and by-products (e.g. combustible gases in the chemical industry) as well as alternative synthetic energy sources (in particular hydrogen and synthetic methane).

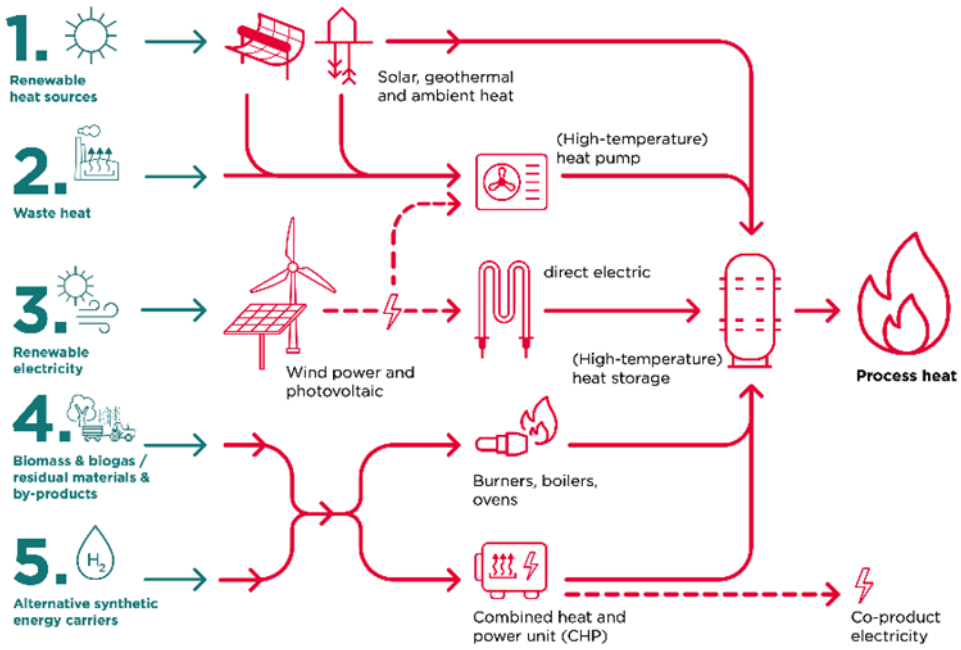


Figure 20: Energy sources and technologies for decarbonized process heat generation, Source: (Schüwer and Holtz, 2023), translated

Although these energy sources and technologies are generally available on the market, they are characterised by different levels of availability (e.g. ramping up of green hydrogen) and technical

maturity (e.g. in the electrification of special technical processes). For example, there is still a need for research into some technologies such as high-temperature heat pumps or heat storage systems, as well as hybrid concepts and the integration of various heat generators into industrial processes.

It is important to bear in mind that not all renewable energy sources are available everywhere and at any time. In addition, not every technology is suitable for every temperature level and every area of application (process, industry). A key challenge is therefore to develop and use customised heat generation solutions for each specific application in accordance with the required temperature level (see Figure 21 or IN4climate.NRW (ed.) 2021, p. 13 - 18).

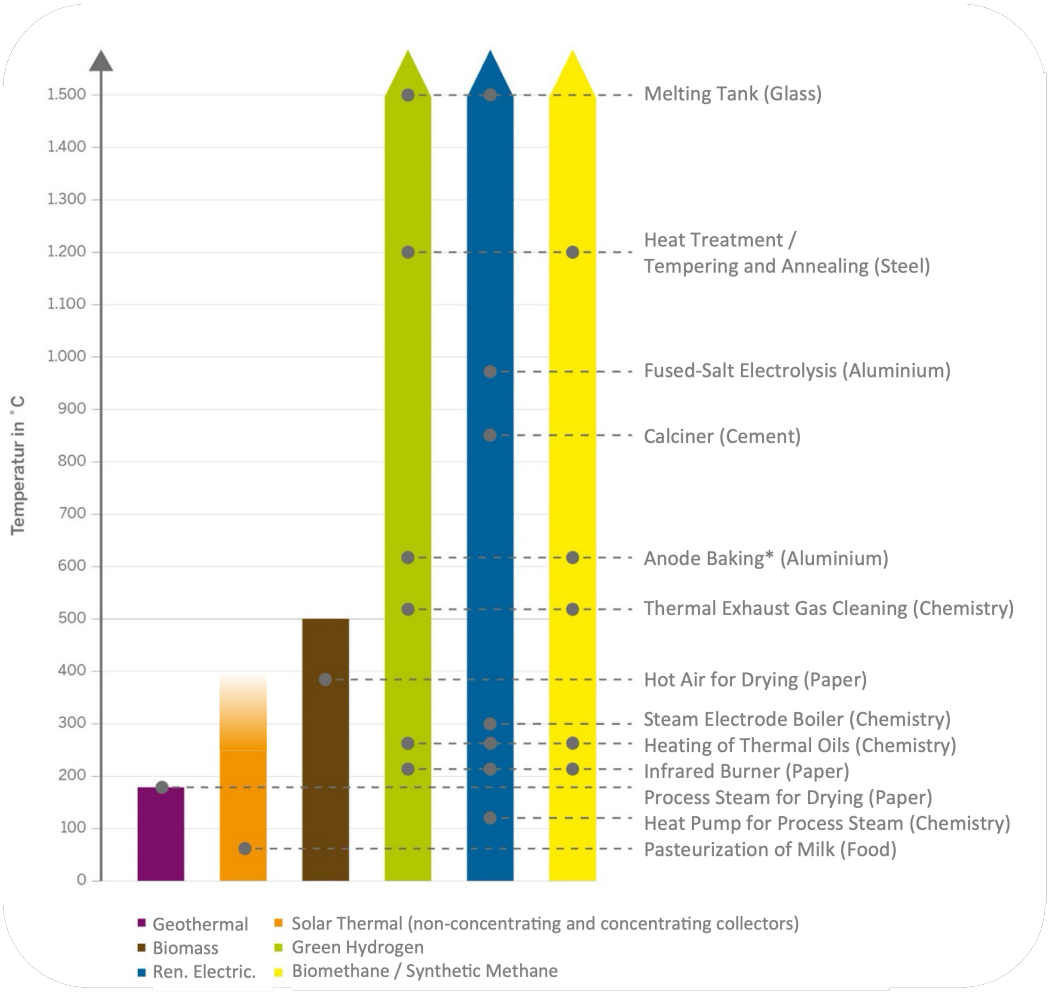


Figure 21: Achievable temperatures and potential areas of application for renewable process heat
Source: IN4climate.NRW (ed.) 2021, updated and translated

4.2.2 THE 4-STEP-MODEL FOR PRIORITISED USE OF TECHNOLOGY OPTIONS

Even if adapted solutions must be found locally, a prioritisation of the provision options can be derived in principle when selecting climate-neutral technology options from the point of view of energy and resource efficiency, which goes beyond a case-by-case consideration. The ***4-Step-Model*** jointly developed by the think tank *IN4climate.NRW* and the scientific competence centre *Sci4Climate.NRW* builds on the above-mentioned technologies and renewable energy sources (Figure 20) for the transformation of industrial energy systems (IN4climate.NRW (ed.), 2021). It can be a good aid in determining the prioritisation of steps that should be taken to decarbonise industrial process heat. The four stages are described in Figure 22.

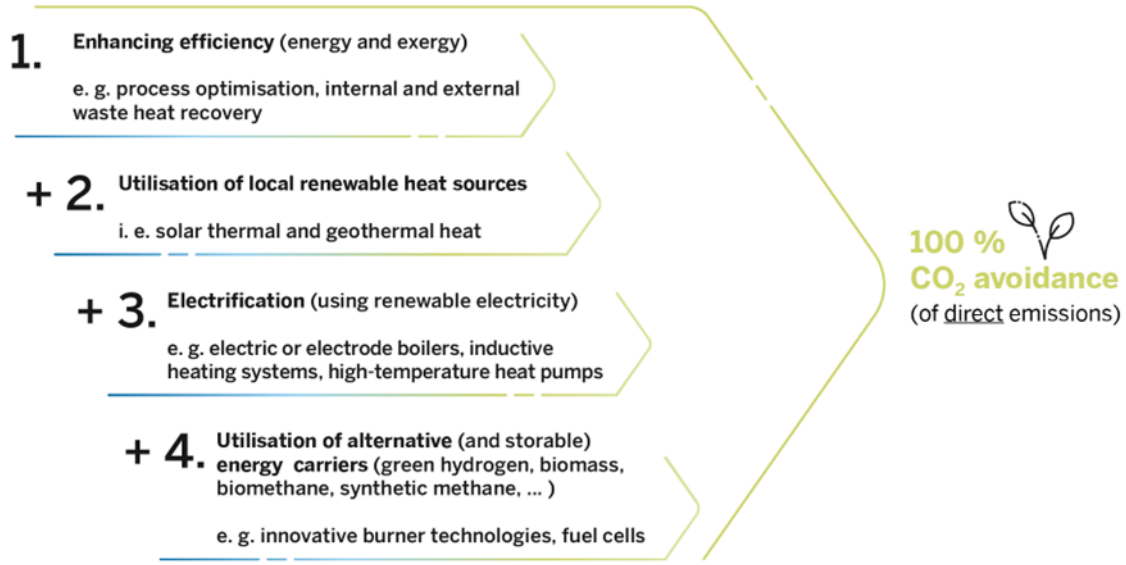


Figure 22: 4-Step-Model of a climate-neutral process heat supply
Source: IN4climate.NRW 2026

1. Increasing energy efficiency

Increasing energy efficiency is a key strategy on the path to GHG neutrality, as it is generally a prerequisite for making do with the locally and systemically limited resources of renewable energies and their transport capacities. It also reduces the risk of high energy prices, both at company level and aggregated in the overall system, in view of the prospect of scarce supplies of greenhouse gas-neutral energy sources. Specific measures include switching from steam to hot water, reducing the temperature and pressure level of the steam supply to the required level, insulation measures, process optimisation and process conversion to new methods as well as the broad field of (internal) excess heat utilisation. Energy efficiency also means that applications at a low temperature level should be supplied with low-temperature heat sources (LT) where possible, whereby heat pumps can raise the heat to the required

temperature level. Conversely, energy sources with a high *exergy content*[1], such as electricity, biomass or gases, should preferably be reserved for high-temperature (HT) applications or for the use in efficient technologies such as heat pumps or CHP systems. In view of high energy prices and the prospect of rising CO_2 prices, energy efficiency measures are often economically attractive over the life cycle, even if they do not always fulfil the expectations of companies in terms of short amortisation periods.

2. Development of renewable heat sources

By developing renewable heat sources on site as far as possible, local potential can be utilised. The technologies in question differ in many respects, so that their development requires a detailed, individual investigation on site, including the analysis of company-specific load profiles and, if necessary, the expansion of transport infrastructures for the supply of renewable electricity.

For the technological options

- **solar thermal collectors** (concentrating and non-concentrating),
- **geothermal energy** (deep and near-surface in combination with heat pumps),
- **ambient heat** (in combination with heat pumps),
- **excess heat** (direct and with heat pumps),

the most important characteristics are described below.

Solar thermal energy efficiently generates process temperatures of up to 80°C (flat plate collectors), 120°C (vacuum flat plate or tube collectors), or 300°C (concentrating parabolic troughs), see Figure 23. Production costs are economically attractive (approx. 50 €/MWh_{th}), particularly for ground-mounted systems exceeding 1000 m² and even in temperate zones like Central Europe. As a quickly deployable fossil-fuel alternative, it requires sufficient space and - due to supply fluctuations - integration with heat storage and backup systems. It is especially suitable for summer-peaking industries (e.g., beverages) and in combination with solar cooling via absorption or adsorption chillers.

[1] *In thermodynamics, exergy is defined as the proportion of energy (depending on the ambient conditions) that can deliver work in an ideal (loss-free) system. For heat, the exergy content is directly dependent on the temperature level in relation to the ambient conditions and can be regarded as a measure of the heat quality (valence). Examples of exergy contents are 7 % for space heat at 20°C, 27 % for process heat at 100°C and 79 % for process heat at 1 000°C (ambient condition: 0°C).*

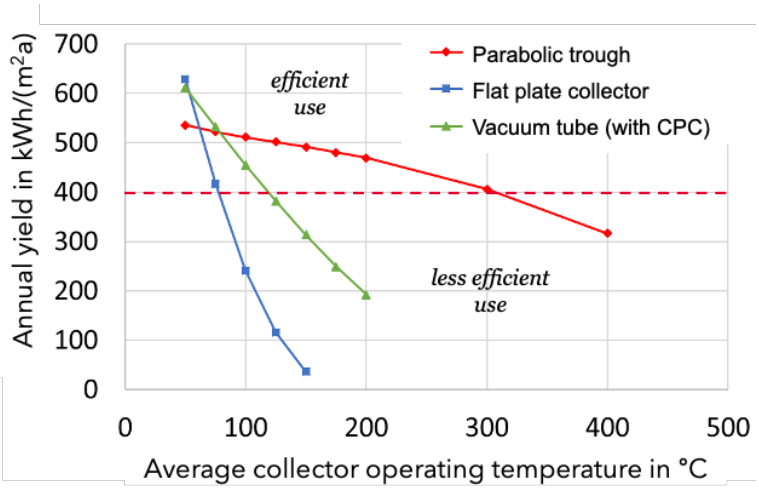


Figure 23: Specific yields of non-concentrating and concentrating solar thermal technologies at the Potsdam/Germany site (CPC = Compound Parabolic Concentrator). Source: (Krüger et al. 2021), own translation and efficiency limit added at 400 kWh/m²a

Deep geothermal energy provides space/process heat and electricity, often via combined heat and power (CHP) plants. This potential is utilized globally (IGA, 2015); by 2018, 88 countries applied geothermal heat directly, and 29 generated electricity (Lund & Toth, 2021). Typical industrial applications include wood or pulp[2] processing, textiles, chemicals, pharmaceuticals, metal/mineral recovery, and desalination (IGA, 2022). In Germany, for example, geothermal temperatures reach 140°C or higher, with a technical potential of 130–150 TWh - roughly one-quarter of national industrial heat demand (Fraunhofer IEG et al., 2022). Despite this promise, commercial development remains in its infancy due to exploration risks, high investments, and regulatory restrictions. However, high CAPEX is offset by low operating costs and base-load capability.

Near-surface geothermal or **ambient heat** combined with electric heat pumps (HPs) is established for space heating. For process heat, temperatures reach 80°C (conventional HPs), 100°C (high-temperature HPs), and 200°C (ultra-high temperature HPs). Efficiency (SPF approx. 200–500%) and Technology Readiness Level (TRL 6 - 9) decrease with higher sink temperatures or temperature stroke. Performance can be improved via cascading, albeit at higher costs. In vapor applications, electric recompressors further increase pressure and temperature levels. Systems reaching 300°C, such as the DLR CoBra project[3], are currently at laboratory scale.

[2] e.g. Geothermal Paper Drying Project: www.umsicht.fraunhofer.de/en/projects/geothermal-paper-drying.html

[3] DLR (2022): High-Temperature Heat Pump CoBra – Technologies for low-carbon industrial processes – Process heat using renewable sources https://event.dlr.de/en/hmi2022-energie/hochtemperatur-waermepumpe-cobra

Unavoidable industrial, commercial or municipal excess heat should be utilised internally in processes or operations or made available externally to third parties. If the temperature level is not sufficient for direct excess heat utilisation, heat pumps can also be used to raise the temperature to a suitable level. According to a study on large heat pumps, a total technical heat potential of 1571 TWh could be tapped in Germany from environmental heat (excluding ambient air) and excess heat via heat pumps. In the temperature range up to 200°C, this significantly exceeds both the overall German heat demand of approx. 1070 TWh and the industrial process heat demand of 199 TWh (Agora Energiewende & Fraunhofer IEG, 2023).

3. Electrification

The electrification strategy—also known as power-to-heat (P2H)—represents a major lever for decarbonisation. A distinction must be made here between the cross-sectional technology for steam generation with heat pumps (efficiency between 200% and 500% depending on the temperature range, see above), electric or electrode boilers (efficiency approx. 98%), and process-related electrification using various technical-physical processes such as resistance heating, inductive, conductive, dielectric, infrared, plasma or arc processes. Many of these processes are ready for the market (TRL of 9) and are superior to other combustion-based processes in terms of efficiency, controllability, and product quality. They are therefore already used as standard, particularly in the high-temperature range, e.g. in secondary steel production, metal processing or glass melting. The electrification of established processes and the introduction of new P2H technologies (e.g. microwave or plasma technology) are expected to be expanded. Switching from gas-based to electrical heat generation may require a considerable expansion of electrical infrastructure such as power lines and transformers.

4. Alternative energy sources

Alternative energy sources are only available to a limited extent in the short term (synthetic, renewable gases) or long term (biomass/biogas) and should therefore, for reasons of resource conservation and efficiency, primarily be used for high-temperature applications and only if the above-mentioned options 1. to 3. cannot be utilised technically, economically, or only be partially utilised.

In the case of biomass and biogases, the sustainable potential available at national and global level is limited and is also subject to high demand-side competition from other sectors, e.g., in the form of material utilisation in construction, in basic chemicals, and for fuel production in aviation.

Hydrogen and its derivatives (ammonia, methanol) and synthetic natural gas (SNG) are particularly important as synthetic, renewable gases (and in some cases also liquids). In the simplest case (H_2), they are produced via electrolysis from water using renewable electricity and, if necessary, refined in further steps or made transportable (e.g., as hydrocarbons). Although the theoretical generation potential on a global scale—especially in the sweet spots of the earth with high solar radiation and high wind speeds—appears almost unlimited, it is uncertain whether, and how quickly, enough imported and domestically produced renewable synthesis gases will become available. In the ramp-up phase, it can

also be assumed that green hydrogen would initially be prioritised for material use, e.g., in the form of ammonia or methanol and would therefore possibly not be available for process heat. Further disadvantages of these energy sources are the high conversion losses, e.g., of approx. 37% for H_2 and 50% for SNG (see Figure 24) when utilised as heat for energy purposes—across the entire chain from generation (from electricity) to transport and use—as well as the uncertainties regarding future purchase prices.

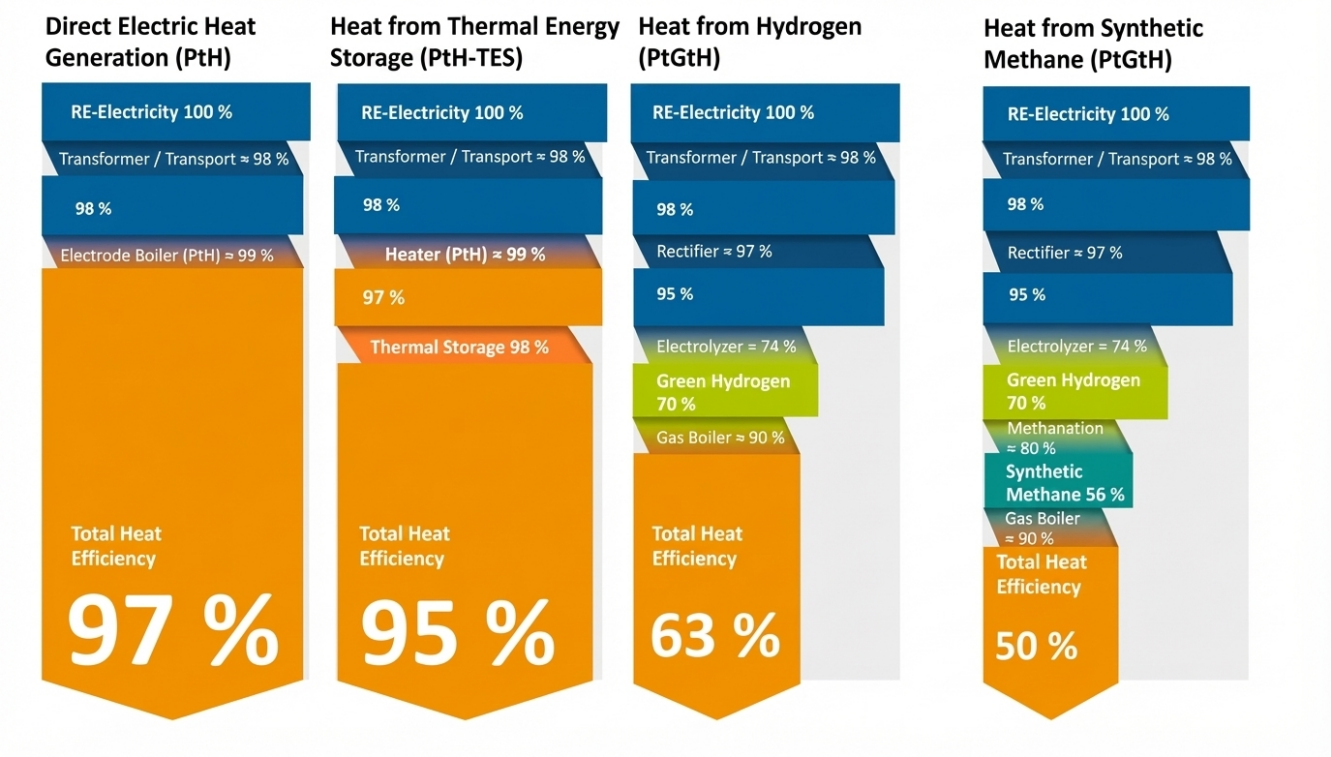


Figure 24: Efficiency chain of power-to-heat (1: without high-temperature Thermal Energy Storage and 2: with TES) compared to power-to-gas (3: hydrogen and 4: synthetic methane) Source: Translation of the IN4climate.NRW graphic in (Schüwer et al. 2023)

CONCLUSION

The stages of the 4-Step-Model model presented here represent test steps that individual industrial companies can go through individually. The prioritisation of these steps follows an overall systemic efficiency approach (Efficiency First) and considers the sometimes high conversion losses of individual energy sources and technologies as well as limited resource availability within and between the sectors. However, location factors and process-related requirements can lead to different results in individual cases. Furthermore, this approach does not necessarily imply an economically optimal solution at company level and does not claim to be able to replace an individual company analysis.

Furthermore, the 4-Step-Model does not reflect all influencing factors and conditions in all sectors. For instance, the thermal utilisation of residual materials and by-products from production, as illustrated in

Figure 22, has already assumed significant importance in the paper and chemical industries. These materials should also be utilised in the future from a resource efficiency perspective. Furthermore, expanding the perspective to include additional aspects such as the possible provision of negative emissions from industry using biomass in combination with CCS can lead to assessments that deviate from the 4-Stage-Model in some places from an overall systemic perspective (see Holtz et al. (2023)).

In principle, however, the 4-Step-Model represents a guideline for the efficient use of limited renewable energies and resources. Policymakers should therefore set the framework conditions in such a way that, ideally, the prioritisation described in the 4-Step-Model also leads to economically viable supply solutions at an operational level as far as possible.

4.3 TRANSFORMATION OF INDUSTRIAL EXCESS HEAT SOURCES

Section 4.2 showed how industrial process heat generation, which is currently based on fossil energy sources, can be transformed in the future in the direction of efficiently utilised renewable energies. This transformation can also have an impact on the future utilisation potential of excess heat. The excess heat potentials analysed in Chapter 3 for today's InES will therefore (have to) change in ways that are not yet clearly identifiable from today's perspective. Before these changes are discussed, section 4.3.1 summarises the findings on excess heat from the literature using a scenario analysis of nine climate protection studies as an example. Subsequently, in section 4.3.2, the changes in excess heat potential caused by industrial transformation are analysed qualitatively.

4.3.1 CASE STUDY: SCREENING ‘EXCESS HEAT’ IN CLIMATE NEUTRALITY STUDIES

This chapter includes translated parts of Schüwer et al. (2024) with the permission of the authors Dietmar Schüwer, Jenny Kurwan and Sascha Samadi.

The results of a meta-analysis on the treatment of the excess heat issue in climate protection scenarios are presented below as an exemplary use case for Germany. The meta-analysis examines eight scenario studies (Scenario 1 to 8), which were published in the period from June 2021 to May 2023 and which relate to the German balancing area. They assume that climate neutrality will be achieved by 2045 at the latest and are compatible with the current German climate protection targets. Only the scenarios analysed in the ESYS meta-analysis are still partly based on the older national climate protection target, which does not envisage climate neutrality until 2050. In addition, the Gexit study (EU Scenario) is used as an example to analyse a scenario with a balance area extended to Europe, which also provides (quantitative) information on excess heat. This study is in line with the European goal of climate neutrality by 2050. Table 4 summarises the respective titles, commissioning and funding bodies, institutes involved, and the names of the scenarios under consideration.

Table 4: List of studies analysed on the topic of excess heat and their climate protection scenarios, Source: Translation from (Schüwer et al. 2024)

Short title & link	Long title	Published	Commissioning / funding body	Author	Climate protection scenarios
German Scenarios					
1) Ariadne Report	Ariadne Report: Germany on the path to climate neutrality by 2045 – scenarios and pathways in a model comparison	Oct 21	BMBF	Ariadne consortium of 13 institutes (including DLR, Fraunhofer, IER, PIK)	6 target achievement scenarios
2) BMWK Long-term scenarios 3	Long-term scenarios for the transformation of the energy system in Germany. Greenhouse gas-neutral scenarios T45	Nov 22	BMWK	Consentec, Fraunhofer ISI, ifeu, TU Berlin	5 scenarios
3) Dena flagship study	dena flagship study – The road to climate neutrality. A task for society as a whole	Oct 21	dena	EWI et al.	Main scenario: Climate neutrality 100 (KN100) with 4 different paths
4) ESYS[1)]	Scenarios for a climate-neutral Germany. Technology transformation, consumption reduction and carbon management	Feb 23	acatech, Leopoldina and Academy Union	Ragwitz, M. / Weidlich, A. et al.	Meta-analysis of 16 scenarios from 7 energy system studies Supplemented by own model calculations
5) Climate Pathways 2.0	Climate Pathways 2.0: An economic programme for the climate and the future	Oct 21	BDI	Boston Consulting Group (BCG)	Target path
6) KNDE 2045	Towards a climate-neutral Germany by 2045. How Germany can achieve its climate targets before 2050	Jun 21	Climate Neutrality Foundation, Agora Energiewende, Agora Verkehrswende	Prognos, Öko-Institut, Wuppertal Institute	Climate-neutral 2045 scenario
7) S4C 2023	Greenhouse gas neutrality by 2045 – A scenario from the SCI4climate.NRW project	Mar 23	MWIKE NRW	Wuppertal Institute and German Economic Institute	SCI4climate.NRW Climate Neutrality (S4C-KN)
8) Greenhouse gas neutral Germany by 2045	New goals using old methods? Strategies for a greenhouse gas neutral energy supply by 2045	Aug 22	FZ Jülich (IEK-3)	FZ Jülich, Institute (IEK-3); Stolten, D./ Markewitz, P. et al.	Target scenario KSG2045
European Scenario					

Gexit[1)2)]	Breaking free from fossil gas. A new path to a climate-neutral Europe	May 23	Agora Energiewende	Artelys, TEP Energy, Wuppertal Institute	EU Gas Exit Pathway

In the meta-analysis, the frequency of mentions of the term "*Excess Heat"* or "*Waste Heat*" (German: "*Abwärme"*), the context in which the topic is dealt with and qualitative and, where available, quantitative statements on excess heat generation and utilisation were examined.

The frequency with which the term excess heat is mentioned varies between '0' (Greenhouse Gas neutral Germany by 2045) and '10' (Climate Pathways 2.0). These figures already suggest a relatively low level of engagement with the topic of excess heat in these climate protection scenarios. Even in the study with the most hits (10), the term is strongly underrepresented in relation to other key technologies, such as heat pumps with 152 hits.

The context of the mention is generally the energy and building sector, i.e., the topic is primarily treated from the perspective of the sink, i.e., the demand for heat and less frequently from the perspective of the source (industrial sector). One study (SCI4Climate.NRW) mentions the utilisation of excess heat in the context of "energy-efficient CO_2 capture in the cement industry (amine scrubbing)". This is therefore an internal utilisation of excess heat, which could become relevant in the context of industrial transformation, but would then possibly reduce the externally usable potential.

4.3.1.1 QUANTITATIVE STATEMENTS FROM THE META-ANALYSIS

Only four of the nine studies analysed make quantitative statements on the future use of excess heat in district heating and two studies on its use in industrial process heat.

For utilisation in **district heating**, the national studies expect growth from approx. 2 TWh in 2018 to 10 to 14 TWh in 2045/2050. In the target years, this corresponds to a share of **6 to 14 %** of total district heating, which covers a not insignificant range of 101 to 164 TWh due to different assumptions regarding the success of demand reduction and the expansion of district heating. The European Gexit study shows shares (for Europe) of 22 to 26% for 2045 and 2050 (of a total of 615 and 585 TWh of district heating, respectively). However, these values are not directly comparable, as this study aggregates excess heat with ambient heat (to an unknown extent). The actual share of utilised excess heat may therefore be significantly lower.

It is worth noting that in the only national study (Climate Pathways 2.0) that provides information on excess heat utilisation in **process heat** (albeit only as a total including district heating), the peak of utilisation is already reached in 2030 at 36 TWh (= 8 % of 444 TWh) and then falls to less than half by 2045 (**15 TWh = 4 % of 366 TWh**). In the study for Europe, on the other hand, the sum of excess heat and ambient heat utilisation in process heat grows continuously to 300 (2045) to 400 TWh (2050) or 10 to 12 % (of a total of 3 150 or 3 300 TWh).

Table 5: Overview of quantitative statements on excess heat development in climate protection scenarios, Source: Translation from (Schüwer et al. 2024)

Excess heat / District heating (DH) / Process heat (PH) in TWh	2018	2030		2045		2050	
	Excess heat	Excess heat	Share of DH/PH	Excess heat	Share of DH/PH	Excess heat	Share of DH/PH
German Scenarios							
Dena Flagship: District Heating	-	**7**	**6 %** (of 124)	**14**	**13 %** (of 109)	**14**	**14 %** (of 101)
Climate Pathways 2.0: District Heating Process Heat[1)]	-	**5** **36**	**3 %** (of 157) **8 %** (of 444)	**10** **15**	**6 %** (of 163) **4 %** (of 366)	-	-
KNDE 2045: District Heating	2	**5**	**3 %** (of 149)	**12**	**7%** (of 164)	**10**	**7%** (of 153)
EU-Scenario							
GExit (EU 27)[2)]: District Heating Process Heat	2 0	**48** **250**	**7 %** (of 710) **8 %** (of 3 050)	**133** **300**	**22 %** (of 615) **10 %** (of 3 150)	**154** **400**	**26 %** (of 585) **12 %** (of 3 300)

1) Gexit study: 'Ambient and excess heat' reported together

2) Climate Pathways 2.0: 'District heating' and 'Excess heat' shown together

Overall, there are only a few (detailed) statements on excess heat in the studies analysed and the few quantitative statements are sometimes vague, for example, because excess heat is subsumed under the term 'heat pump' or because 'ambient heat and excess heat' (Gexit, see above) or 'district heating and excess heat' (Climate Paths 2.0) are shown in aggregated form.

4.3.1.2 QUALITATIVE STATEMENTS FROM THE META-ANALYSIS

For **heat generation**, the studies analysed expect the use of excess heat to be part of a site-specific and individual combination of different heat sources. Other new and renewable heat sources will therefore include geothermal energy, solar thermal energy, (large-scale) heat pumps, electrode boilers (power-to-heat), biomass, and green hydrogen-fuelled CHP plants in conjunction with heat storage systems (Sc. 5). For defossilised district heating, both the share of renewable heat and the contribution of excess heat must increase according to the present scenarios. It is unanimously expected that large heat pumps with ambient and excess heat as heat sources will play an important role in the decarbonisation of district heating. (Industrial) excess heat can be both a heat source for large heat pumps or, if used directly and at a correspondingly high temperature level, alternatively reduce the use of heat pumps (Sc. 2).

In **industry**, excess heat utilisation is seen as a classic energy efficiency measure for industrial processes. One specific example cited is the reduction of specific energy requirements in glass production through excess heat recovery (Sc. 4). However, industrial heat pumps enable the activation of (low-grade) ambient heat or recycled excess heat up to a temperature level of around 200°C, so that efficiencies of well over 100 % can be achieved (Sc. EU). It is pointed out that all industrial heat generators in Germany must be replaced by a renewable solution to achieve the goal of GHG neutrality

(Sc. 5)[4]. For temperatures up to around 130°C, the authors of Sc. 5 consider the use of industrial heat pumps and connection to district heating or industrial excess heat to be the most favourable option. It is therefore expected that by 2030, many industrial processes will be electrified using heat pumps and electric boilers, particularly in the low and medium temperature range, in some cases combined with the utilisation of excess heat (Sc. EU).

Low-temperature direct air capture plants (with a heat requirement in a temperature range of 80 to 120°C) are seen as **new applications** for both district heating and excess heat, which can either be supplied directly with excess heat from industrial and power plant facilities or alternatively with high-temperature heat pumps (Sc. 3). In the future, so-called heat storage power plants (power-to-heat-to-power) with high-temperature heat storage could also be used as an alternative to hydrogen-fuelled power plants (power-to-gas-to-power). Their overall efficiency (utilisation of electricity *and* heat) in the electricity-to-electricity chain is between 30 and 80 %, depending on the degree of excess heat utilisation (Sc. 3). Another new application identified in a study is the utilisation of excess heat for the regeneration of amine scrubbing-based CO_2 capture (Sc. 7). Specifically, for two of the three clinker production sites in southern Germany that remain in the scenario in the longer term, it is assumed that 50% of the CO_2 produced will be captured in an energy-efficient manner by 2045 using excess heat within the site (a total of approx. 450 000 tons of CO_2). In this specific case, this would mean that any current potential for releasing excess heat to heating networks would be eliminated by using CCS.

The promotion of various generation technologies and the expansion of the heating network are recommended as **policy instruments** for the decarbonisation of district heating (Sc. 5). Large-scale heat pumps, biomass, geothermal energy, large-scale solar thermal energy, the connection of (industrial) excess heat and finally the district heating grid conversion itself (including temperature reductions) should be addressed. In addition, it is proposed that successively increasing minimum shares of renewable energies and excess heat in district heating systems be made mandatory (Sc. 1). In principle, the need to tap excess heat potential from industry, buildings, and wastewater to achieve climate protection targets is recognised (Sc. 5). The climate protection target of climate neutrality by 2045 (instead of 2050), which has been brought forward for Germany, requires a faster market ramp-up of excess heat utilisation compared to the past.

None of the studies examined were able to identify specific statements about the expected **impact of the industrial transformation** in the context of decarbonisation **on future excess heat potentials** (in the right-hand column). This means that the studies do not specifically discuss how the excess heat potential will change in the future because of the necessary far-reaching changes in industrial

[4] Note: Current forecasts from climate studies show that CCSU technologies will also have to play a certain role in meeting climate protection targets. According to Kazlou 2024, a portion of global GHG emissions must be removed from the atmosphere using CCS. www.nature.com/articles/s41558-024-02104-0

processes. However, indirect conclusions can be drawn, e.g., from the statement in the studies that (large) heat pumps are ascribed an important role in the decarbonisation of both district heating and industrial process heat. In addition to ambient heat and geothermal heat, excess heat can therefore become a central heat source for the use of heat pumps in the future.

4.3.1.3 CONCLUSION OF THE ANALYSIS

The volume of excess heat and its potential utilisation is only marginally considered in the scenario studies analysed. The analysis is made more difficult by the fact that some studies subsume excess heat under the term ‘heat pump’ or aggregating ‘ambient heat and excess heat’ or ‘district heating and excess heat’. The few studies that explicitly and quantitatively consider the role of excess heat suggest that excess heat utilisation could and should be expanded in the future and that it can play a significant role in achieving climate neutrality, at least in district heating generation. The scenario studies analysed (see Table 6) do not deal in any depth with the question of how excess heat potential will change as part of the upcoming transformation of industry. However, in view of the far-reaching changes that are imminent, it seems very sensible to take a closer look at this research question.

The results of the qualitative meta-analysis can be found in Table 6.

Table 6: Overview of qualitative statements on excess heat development in climate protection scenarios, Source: Translation from (Schüwer et al. 2024)

Study	Context / Chapter	No. of mentions	Qualitative statements	Impact of ind. transformation
1) Ariadne Report	Heat transition (instruments and measures)	1	Proposal to gradually introduce **minimum shares of renewable energies and waste heat** in district heating systems (p. 106)	No mention of "waste heat" in the chapter on industry
2) BMWK Long-term scenarios Slide sets / reports **a) Energy b) Industry c) Buildings**	a) Scenario comparison: heating networks (Germany/Europe) b) Methodology c) N/A	1 1 0	a) Slide set Energy industry: "Other heat sources such as industrial waste heat could further **reduce the need for large heat pumps**" (F56) b) Slide set & report on industry: Graphic on the methodology of the FORECAST simulation model: **Industry with** (unspecified) **effects on** the **"interfaces" "Waste heat** potential" (as well as other "CCS, regional analysis and hourly load curve & DSM") c) The term "waste heat" does not appear	see qualitative statement b)
3) dena flagship study	Energy sector (renewable energy demand and generation)	3 (+5 in brief report)	"In order to provide **climate-neutral district heating in the long term**, **individual combinations of new heat sources** such as geothermal energy, solar thermal energy, industrial **waste heat**, large heat pumps and power-to-heat (electrode boilers) as well as biomass and hydrogen will be used." (p. 110) Brief report "**Technical sinks**": The temperature level of **LT-DAC systems** (80–120°C) can be provided either by waste heat from industrial and power plant facilities or by HT heat pumps (pdf p. 575 f.). Brief report on "**Innovative Technologies**": **Overall efficiency** of **HT storage systems** (30–80%) depending on the degree of waste heat utilisation (pdf p. 748) Waste heat and waste water as **non-renewable heat sources** for **large heat pumps** (pdf p. 769)	No keyword "waste heat" in the industry chapter
4) ESYS a) Buildings b) Industry	Scenario meta-analysis: Energy demand in the area of a) Buildings (district heating) b) Industry	3 2	Increased use of district heating, especially in **conurbations**; in addition to renewable heat sources, these can **also** incorporate **waste heat**, primarily **from industry and wastewater**. (p. 49) **No graph on district heating structure**, only footnote for 2045: 50% large heat pumps / 20% CHP plants (synthesis gas) / remainder: solar thermal energy or surplus electricity (via large heat storage facilities) (p. 82) Waste heat utilisation as **an energy efficiency measure** for industrial processes (pp. 54, 58) Reduction of specific energy requirements in **glass production** (efficiency increase through waste heat recovery) (p. 157)	No keyword "waste heat" in the industry chapter
5) Climate Pathways 2.0 a) Energy (DH) b) Industry	a) Energy sector (district heating) b) Industry (industrial heat)	10	a) For defossilised district heating, the **contribution of waste heat must increase**, among other things: "The district heating of the future will be generated **locally** using a **combination of various waste heat sources**, heat pumps, solar thermal energy, geothermal energy and biomass, as well as green hydrogen-powered CHP plants in conjunction with heat storage and power-to-heat." (p. 167) **Waste heat potential** from industry, buildings, wastewater and rivers must be tapped (p. 168). The study recommends the following **political instruments** for decarbonising district heating: "Federal funding for efficient heating networks (**BEW**) should promote various generation technologies and network expansion. Large heat pumps, biomass, geothermal energy, large-scale solar thermal energy, **connection of (industrial) waste heat** and, finally, the district heating network conversion itself (including temperature reductions) should be addressed here." (p. 177) b) Heat generation for **industry**: In order to achieve GHG neutrality, all industrial heat generators in Germany must be replaced by a renewable solution: For low **temperatures up to around 130°C**, the use of industrial **heat pumps** is the most cost-effective option, as is **connection to district heating or industrial waste heat** (p. 15).	No connection is made
6) KNDE 2045	Energy sector (DH generation)	2	"The use of **waste heat** is also increasing. Here too, the **KN2045** scenario expects a **faster market ramp-up** than the **KN2050** scenario." (p. 40)	No keyword "waste heat" in the industry chapter
7) S4C 2023	Use of waste heat for energy-efficient CO_2 capture (cement industry)	1	For two of the remaining three **clinker production sites** in southern Germany, it is assumed that **amine scrubbing-based CO2 capture** will be carried out in an energy-efficient manner **using waste heat**, thereby capturing 50% of the CO2 produced (total in 2045: approx. 450 kt CO2).	See qualitative statement
8) Greenhouse gas-neutral Germany by 2045	-	0	N/A	No connection is made
EU) Gexit a) Energy (DH) b) Industry	a) Energy sector (district heating) b) Industry	2 4	a) The increase in renewable energy and waste heat is helping to **replace fossil gas in district heating generation**. **Large heat pumps** using ambient and **waste heat as heat sources** play an important role in the **decarbonisation of district heating**. **b) Industrial heat pumps** are capable of **efficiently utilising** ambient heat or recycled **waste heat**, enabling them to activate more thermal energy (**up to around 200°C**) than they consume in electricity and achieve **efficiencies** of **over 100%** (p. 33). **In the low and medium temperature range in particular**, many **industrial processes** will be electrified **by 2030** through the use of **heat pumps** and electric boilers, **in some cases combined with** the use of **waste heat** (p. 36).	No connection is shown.

4.3.2 IMPACT OF INDUSTRIAL TRANSFORMATION ON EXCESS HEAT POTENTIAL

This analysis of the impact of industrial transformation on excess heat potentials is, in large, a translation of (Schüwer et al., 2025) with the permission of the authors Dietmar Schüwer, Georg Holtz, Simon Block and Alexander Scholz.

When assessing the potential for future excess heat utilisation, it is important to consider the impact of industrial (process heat) transformation on the future availability and usability of excess heat. This is important both for determining how much excess heat can be recycled internally within companies (or clusters) in the future—particularly using high-temperature heat pumps—and how much can be transferred externally to third parties.

Analyses of climate protection scenarios for Germany and Europe (e.g., Agora Energiewende, 2019, 2023; Agora Think Tanks, 2024; Consentec et al., 2024) show that achieving climate neutrality will require a fundamental restructuring of all sectors (energy, transport, buildings, industry and agriculture, see also Chapter 4.3.1 Case study: Screening of 'excess heat' in nine climate neutrality studies). The strategies required to achieve climate neutrality in industry are largely known, and in many cases the necessary technologies are already commercially available. Key strategies include the implementation of **energy efficiency** measures, increased **internal excess heat utilisation**, a switch to **renewable energy** sources, and the use of **carbon capture and storage**. In addition to the actual decarbonisation (switch to non-carbon-based energy sources) or defossilisation (switch to non-fossil carbon-based energy sources) of process heat, several other effects of the energy and industrial transformation are also affecting industrial structures. These may result from future changes in **production volumes**, **product** or **process changes,** and **new applications** relevant to process heat.

Overall, the following aspects of industrial and energy transformation are considered about their potential impact on the future development of excess heat potential:

1 | **Changes in production volumes**

through sufficiency and energy efficiency in demand, material efficiency and circular economy in production, substitution with other products (product change), and relocation of production to/from abroad

2 | **Process change**

through fundamental change in the entire process chain

3 | **Climate-friendly process heat generation**

through energy efficiency measures in the manufacturing process (excluding process change, point 2) and
switch to renewable energy sources (excluding process change, point 2)

4 | New applications as excess heat sources

- Power-to-X synthesis (PtX)
- CO_2 capture from industrial plants (Carbon Capture)
- CO_2 capture from the air (Direct Air Capture, DAC)
- Data centres[5]

The individual influencing factors outlined above are examined in more detail in sections 4.3.2.1 to 4.3.2.4. Their mechanisms of action are explained, and finally their anticipated effects on future excess heat utilisation are assessed qualitatively. The results are summarised in Table 7 and in the subsequent summary and conclusion.

Table 7: Influencing factors and effects of industrial decarbonisation using industrial excess heat

Influencing Factor	Impacts	Trend Excess Heat Potential
Production Volumes	• Declining primary production through sufficiency, energy and material efficiency, circular economy • Product change: Phase-out of fossil-based products (e.g. heating oil, petrol) • Renewables pull: Import / Export of energy-intensive products (e.g. sponge iron DRI or ammonia)	↓ ↘ ↓ ↘ / ↑ ↗
Process Change	• Phase-out of excess heat-intensive processes (e.g. replacement of blast furnace route with H_2 direct reduction plant, additive manufacturing of turbine blades in 3D printer instead of metal casting)	↓ ↘
Electrification	• Significant improvement in efficiency: better dosing, no exhaust gases (e.g. electric calciner in cement clinker production)	↘
Renewable Heat	• Lower excess heat flows if combustion processes are completely or partially replaced by deep geothermal energy or solar thermal energy • Possibly (temporary) additional usable potential from renewable surplus heat • Consistent excess heat flows when using biogenic or synthetic renewable fuels	↘ ↗ →
PtX Synthesis	• Potentially high additional excess heat potentials in H_2 production (electrolysis) and the provision of synthetic hydrocarbons (methanol synthesis, Fischer-Tropsch process)	↑
iCCS/CCU DAC	• Depending on the process, higher heat and/or electricity demand: If heat requirements are higher, use of (previously unused) excess heat streams instead of transferring excess heat to third parties (e.g. in Post-combustion carbon capture or low-temperature Direct Air Capture). • Pre-combustion & Oxyfuel carbon capture: No or only minor impact on excess heat flows	↘ →
Data Centres	• New and more powerful data centres, including new high-temperature cooling technologies	↑

iCCS: Industrial Carbon Capture and Storage, CCU: Carbon Capture and Usage, DRI: Direct Reduced Iron, DAC: Direct Air Capture

Legend to the effects of an influencing factor on future excess heat potential: Indicator leads to ...

↑ (arrow 90° up) *significant increase in excess heat potential*

↗ (arrow 45° up) *moderate increase in excess heat potential*

→ (arrow sideways) *Approximately unchanged excess heat potential (or unclear effects)*

[5] Data centres do not fall under industrial applications, but rather commercial applications. However, they are considered here due to their high and likely increasing relevance in terms of their excess heat potential.

↘ (arow 45° down) *Moderate reduction in excess heat potential*
↓ (arrow 90° down) *Significant reduction in excess heat potential*

Overall, effects of industrial transformation on excess heat potentials are complex: both **reinforcing** and **mitigating factors** influence the potential for industrial excess heat in connection with the decarbonisation of industry.

Mitigating factors include **sufficiency** in product demand, **energy efficiency** in product application (e.g., of fuels and propellants) and success in the **circular economy** and in **material efficiency** in production. The latter mean that fewer primary raw materials are (or need to be) produced.

Since **electrification** is usually accompanied by a significant increase in efficiency, this important climate protection measure is also expected to reduce the amount of excess heat.

Radical **process changes** (e.g., the switch from blast furnace production to direct reduction iron (DRI) in the steel industry), the complete **phase-out** of **fossil products** (e.g., heating oil, petrol), or increased **imports** of **energy-intensive** raw **materials** or intermediate products (such as sponge iron or ammonia) can also lead to losses in excess heat potential from the associated production processes. Conversely, the renewables pull effect in future **export** countries for green intermediate products may also lead to new production and thus increasing excess heat potential.

However, some of the losses are at least partially offset by the production of new synthetic products **(PtX synthesis)**. The extent to which these new applications replace existing excess heat potential or create new potential depends largely on the future domestic production volume of PtX products, the processes used, and the internal heat integration in complex plant structures.

When using **renewable heat**, lower excess heat flows can generally be expected if combustion processes are completely or partially replaced by deep geothermal energy or solar thermal energy. If fossil fuels are replaced by biogenic or synthetic renewable fuels, this has little effect on excess heat potential.

The effects of using new applications such as **carbon capture** from industrial plants (**iCCS/CCU**) or from the air (Direct Air Capture, **DAC**) depend on the specific process configurations and their boundary conditions and require a case-by-case assessment. For example, amine scrubbing (post-combustion), a carbon capture process suitable for retrofitting, and low-temperature direct air capture are both heat-intensive processes that could compete with free excess heat in the future.

Not directly linked to industrial transformation is the expected rapid expansion of new and more powerful **data centres**. Strong growth potential is forecast for this reliable and constant source of excess heat in the future. The use of new high-temperature cooling technologies can also improve the temperature level and thus the quality of excess heat from data centres.

The analysis shows that excess heat can continue to play an important role in the decarbonisation of heat generation in the future. However, when developing specific excess heat projects, the influencing

factors examined here and their potential impact on future changes in potential should be considered to ensure long-term economic viability.

4.3.2.1 CHANGES IN PRODUCTION VOLUMES

This indicator can be used to identify a whole range of factors relevant to transformation, such as sufficiency, energy efficiency, production relocations (to or from abroad), material efficiency and circular economy, as well as substitution by other products (product change)[6] .

On the demand side, this could be, for example, lower demand due to **sufficient** or **energy-efficient behaviour** in the areas of housing and consumption (lower demand for heating fuels, living space or consumer goods) or transport (lower demand for fuels due to more efficient vehicles or lower mileage). On the production side**, material efficiency**, i.e., the question of how much or how little material is needed to manufacture a product with a specific function, has just as much influence on production volume as the **circular economy** within product manufacturing and the product life cycle. A higher steel recycling rate, for example, means that in steel production, the so-called secondary route (melting steel scrap in an electric arc furnace) is gaining importance over the more energy- and greenhouse gas-intensive primary route (steel production in a blast furnace). Sufficiency, efficiency, and circular economy will tend to increase in the context of the energy system transformation, so that these influencing factors will lead to a reduction in (primary) material requirements and thus to a reduction in production volumes and the amount of excess heat associated with production.

In addition, there are dynamics whose effects on excess heat availability depend on the individual case. When **changing products** (substituting products), the decisive factor is ultimately the excess heat potential of the respective production processes. Examples of product changes in the context of the energy transition include the phasing out of fossil refinery products such as petrol, diesel or kerosene and their replacement, e.g. by electricity or hydrogen, or the (partial) substitution of plastic- or cement-based materials such as packaging, insulation materials or concrete components by plant fibres or wood. **Production relocations** (to or from abroad) lead to changes in the (domestic) production volumes of products or intermediate products and thus to shifts in the amounts of excess heat associated with production. Prominent examples are the use of climate-neutral sponge iron (DRI) produced abroad instead of domestically produced pig iron, or imported green ammonia instead of domestically produced ammonia. This phenomenon of the potential relocation of production processes

[6] Other determining factors such as *economic growth* or *the ratio of imports to exports* are not considered here, as they are not directly related to the energy transition or industrial transformation.

or parts thereof to regions with more favourable renewable energy generation potential is also discussed in the literature under the term "*Renewables Pull*" (Samadi et al., 2023; Verpoort et al., 2024) .[7]

Potential effects on excess heat utilisation:

- Reduced production volumes due to sufficiency in product demand, energy efficiency in product application, and material efficiency and circular economy in product manufacturing: ↘ to ↓
- Substitution by other products (product change): ↘
- Relocation of energy-intensive production to/from other countries: ↓ (importing countries), ↑ (exporting countries)

4.3.2.2 PROCESS CHANGES

Process changes refer to the conversion of an entire manufacturing or processing procedure (process chain). The conversion of individual units from fossil-based to greenhouse gas-neutral production of process heat (e.g. steam generators, burners or furnaces) is discussed below in section 4.3.2.3 "Climate-neutral process heat generation".

Process changes include breakthrough technologies from the basic materials industry. In the **steel industry**, for example, the DRI route (production of directly reduced iron using climate-neutral hydrogen) has the potential to completely replace the greenhouse gas-intensive blast furnace route (pig iron production using coking coal). Alternatively, the blast furnace route could also be replaced by electricity-based electrolysis of iron ore dissolved in caustic soda, followed by further processing in an electric arc furnace to produce crude steel.

One example from the **chemical industry** is the conversion of the steam cracker route (based on fossil naphtha) to green methanol as a synthetic platform chemical for plastics production. This conversion enables largely climate-neutral production of the basic building blocks for plastics from the olefin group (methanol-to-olefin route = MtO) and aromatics (methanol-to-aromatics route = MtA).

Another example of a fundamental process change is **additive manufacturing** (AM), e.g., of turbine blades for gas and steam turbines. This laser sintering process in a 3D printer replaces conventional production methods such as casting, forging and milling.

Since the actual impact of a process change on the potential for excess heat utilisation can vary greatly from case to case, it is difficult to make a general statement. However, since climate-neutral energy sources (e.g. electricity or hydrogen) tend to be expensive compared to fossil fuels, it is likely that, in

[7] Conversely, the renewables pull effect in future export countries for green intermediate products (such as DRI or ammonia) may also lead to new production and thus increasing excess heat potential.

the context of energy and industrial transformation, those process innovations that enable particularly energy-efficient climate-neutral production will prevail. It can therefore be deduced that excess heat potential – as a measure of the efficiency or inefficiency of processes – will tend to decline.

Potential effects on excess heat utilisation:

- Process change: ↘ to 🡻 (depending on the individual case)

4.3.2.3 CLIMATE-NEUTRAL PROCESS HEAT GENERATION

INCREMENTAL ENERGY EFFICIENCY MEASURES

Incremental energy efficiency measures are understood here—in contrast to radical innovations in the form of process or product changes (see sections 4.3.2.2 and 4.3.2.1)—as measures for the gradual improvement of the efficiency of existing processes. This increase in energy efficiency is an essential strategy on the path to greenhouse gas neutrality, as it is usually a prerequisite for making do with limited local and systemic renewable energy resources and their transport capacities. It also mitigates the risk of high energy prices and dependence on imports, both at the company level and across the entire system.

Specific measures include switching from steam to hot water (where technically feasible), reducing temperature and pressure levels in the steam supply to the necessary minimum, thermal insulation, thermodynamic process optimisation (e.g., through improved burner design or optimised process control) and the internal use of excess heat through increased heat integration.

It can generally be assumed that any increase in the efficiency of a process will lead to a higher proportion of useful energy in the final energy used and thus to a reduction in the use of final energy and a pronounced reduction in excess heat potential.

Potential effects on (external) excess heat utilisation:

- Energy efficiency measures: ↘

SWITCH TO RENEWABLE ENERGY SOURCES

The conversion of process heat generation to renewable energy sources (including the use of residues and by-products) is the central strategy for covering the remaining energy demand in a climate-neutral manner after efficiency improvements.

Options include renewable heat sources (e.g., solar thermal energy), unavoidable excess heat, renewable electricity, biomass (including biogas), residues (e.g. from the paper industry) and by-products (e.g., combustible gases in the chemical industry) as well as alternative synthetic energy sources (in particular hydrogen and synthetic methane), see Figure 20 (Energy sources and technologies for decarbonised process heat generation) and Figure 22 the “The 4-Step-Modell”.

When considering the impact of a switch to renewable energy sources on excess heat utilisation, the most relevant factor is the type of process heat generation that is being replaced by the switch. If the initial process is a combustion process (efficiency in the range of 70 to 95 %)[8] , which inevitably involves excess heat losses, the excess heat potential will only remain approximately the same if there is a switch to the combustion of renewable fuels. Substitution with renewable heat or renewable electricity (electrification) eliminates a significant portion of the excess heat potential, namely the losses caused by combustion and exhaust gases.

Renewable heat

The technology options for using renewable heat include *solar collectors* (concentrating and non-concentrating), *geothermal energy* (deep and near-surface, in combination with heat pumps) and *ambient heat* (in combination with heat pumps). All three technologies or energy sources can be expected to replace (completely or partially) process heat generators based on fossil fuels, and in this respect lower (combustion-related) excess heat flows. Additional usable potential may also arise (temporarily) from renewable surplus heat if the heat supply from solar radiation (e.g., in summer) or deep geothermal energy exceeds the current heat demand and cannot be buffered, or cannot be fully buffered, in heat storage systems.

Potential effects on excess heat utilisation:

- Solar collectors, geothermal energy, or ambient heat: ↘
  (when replacing combustion processes)
- Solar collectors or deep geothermal energy: ↗
  (in the case of temporary renewable heat surpluses)

Renewable electricity (electrification)

Electrification, also known as power-to-heat (PtH), is a key lever for decarbonising industrial process heat. Here, a distinction is made between heat pumps (with an efficiency of around 200% to 500%, depending on the temperature difference, Arpagaus (2019)) and electric or electrode boilers (with an efficiency of approx. 98%) in the cross-sectional technology *of steam generation*.

In addition, process-related electrification encompasses various industry-specific technical and physical processes such as resistance heating, inductive, conductive, dielectric, infrared, plasma and arc processes. Some standard electrical applications are technically limited in terms of their use at very high temperatures (> 1000°C) and/or in terms of their power density. Electrical resistance heating elements,

[8] Combustion efficiencies of approx. 70–85% for various furnaces and heat treatment processes (Fleiter et al., 2023) and up to 95% for steam boilers.

for example, have a significantly lower power density than natural gas burners. Nevertheless, it is expected that the share of electrification in established processes will continue to grow and that new PtH technologies, such as microwave or plasma technology, will be introduced. (Fleiter et al., 2023; Görner & Lindenberger, 2018; Pfeifer, 2013).

A basic distinction is made between direct and indirect electrical heating processes. In *direct* processes (inductive, conductive, dielectric), the conversion into heat takes place directly in the workpiece itself. In *indirect* processes (such as resistance, arc, or infrared heating), the conversion into heat takes place outside the workpiece. The heat is then transferred to the surface of the workpiece, either by a heat transfer medium (such as air, steam, liquid baths), by heat conduction and convection, or by heat radiation (infrared). The type of electrical heating process has a significant influence on efficiency and thus on the potential excess heat flows in the process.

If the temperature level allows, internal excess heat utilisation is already practised in many energy-intensive processes. An example from the foundry industry is the fuel-fired hot blast cupola furnace for *internal* process recovery for hot blast generation or via thermal oil for *internal* recovery for other areas of operation. In contrast, when switching to an electric induction furnace, operational use—except for hot water production—is practically impossible because the driving temperature difference is too small (Fleiter et al., 2023, p. 171).

Potential effects on (external) excess heat utilisation:

(For details, see the penultimate column in Table 8)

- Electrification of various furnaces and processes in the metal and mineral industry: ↘
- Electrification of steam generators: 🡻

Renewable gaseous, liquid, or solid fuels

Renewable hydrogen and its derivatives (e.g., ammonia or methanol), biogas, and renewable synthetic methane (SNG)[9] are particularly suitable substitutes for natural gas. Since SNG has almost identical properties to natural gas and generally does not require any technical modifications to heat generators, it will not be considered further here. Sustainably produced *biogas* is and remains a scarce resource, and renewable *hydrogen* is also not (yet) available in large quantities and at low cost. For efficiency reasons, these green gases should be used where electrical alternatives are not technically or

[9] SNG = Synthetic Natural Gas

economically feasible, i.e., in the maximum temperature range or in applications where high heat transfer density is required (e.g., in large glass tanks).

Liquid alternative fuels play a minor role in energy use and will be more relevant in the future in the transport sector as fuels for drives that are difficult to electrify (ships and aeroplanes).

Solid biomass can be used to generate steam in boilers or for industry-specific applications such as rotary kilns in the cement industry. *Bio-coke* is a special case, which can be used, for example, in the continuous melting of cast iron ($T_{melt,max}$ ≈ 1 580°C) in hot-blast or cold-blast cupola furnaces instead of fossil coke. The impact of switching from fossil to biogenic coke on excess heat generation depends on the composition and efficiency of the fuel. (Fleiter et al., 2023, p. 102 f., 171)

Potential effects on excess heat utilisation:

- H_2 use in furnaces and processes in the metal and mineral industry: ➔
- H_2 use in steam generators: ➔
- Biomass/bio-coal use: ➔ (depending on fuel quality)

Table 8 Exemplary excess heat generation with natural gas heating and impact of switching to electricity or hydrogen (average values for individual plants)

Industry	Processes	Furnace type	Excess heat		Impact	
			Volume flow [m³/h][1)]	Temp. [°C]	Electrification	H_2 use
Metal industry						
Heating and annealing furnaces Steel rolling mills	Heating and heat treatment (flat/long steel)	Tilting beam, push, roller hearth, continuous annealing and bell annealing furnaces	1 000 – 77 500	200 – 450	↘	→
Foundry industry	Melting: Cast iron[2)] and aluminium alloys	Hot blast, cold blast, cupola, shaft furnace	8 000 – 120,000	<100 (after filter) to <300	↓	↘
Non-ferrous metal industry (aluminium)	Melting/holding, homogenisation/heating, heat treatment	Chamber furnace, batch furnace, (roller) continuous furnace, chamber furnace, suspended belt furnace	755 – 45 000	150 – 300	↘	→
Non-ferrous metal industry (copper)	Melting, heating, heat treatment	Cathode shaft, walking beam, roller hearth, bell furnace	<1 400 – 24 000	140 – 400	↘	→
Forming technology (solid forming and press hardening)	Heating, forging[3)], press hardening	Continuous, rotary hearth, bogie hearth, chamber forging, roller hearth furnace	10.6 - 11.5 m³ exhaust gas / m³ natural gas	400 – 500	↘	→
Hardening technology	Carburising and austenitising	Push-through, belt and chamber furnaces	155 – 2 750	400 – 450	↘	→

Mineral industry						
Glass industry including glass fibre	Melting (container glass and flat glass)	U-flame furnace, cross-burner furnace (regenerative)	10 m³ exhaust gas / m³ natural gas	400 – 800	↘	→
Lime industry	Burning of lime[4)]	Normal shaft, GGR, rotary kiln	6 000 – 160 000	100 – 220	n.a.	n.a.
Cement industry	Burning of cement clinker	Rotary kiln (including calciner) Clinker cooler	1.7 – 3 m³/kg clinker 0.89 m³/kg clinker	90 – 180[5)] 245	↘	→
Ceramics and brick industry	Firing of bricks / refractory materials	Tunnel kilns, bogie hearth kilns	Exhaust gas: 8 000 – 50 000 Cooling air: 3 000 – 15 000	100 – 350 200 – 500	↘	→
Steam generator						
Food industry	Milk powder production	Drying up to 240°C (~25 bar)	-	-	↓	→
Paper industry	Paper drying	Drying up to 140–150°C (~3–6 bar)	-	-	↓	→
Chemical industry	Chemical park Steam supply	Low, medium and high pressure	-	-	↓	→

[1)] Based on standard temperature and pressure (STP)
[2)] Coke instead of natural gas heating
[3)] Based on the fossil fuel-heated portion that cannot be heated inductively (most of the parts forged in the die are heated inductively).
[4)] Depending on the application, heating with coke, lignite dust, secondary fuel or natural gas
[5)] Depending on use in the raw mill (pre-drying)

Source: Own compilation with table data from (Fleiter et al., 2023)

4.3.2.4 NEW APPLICATIONS

In addition to the substitution of energy sources, products, and processes, the energy transition is also giving rise to completely new applications relevant to process heat. These include the ramp-up of synthetic renewable energy production in power-to-X (**PtX**) plants, the capture of process- and fuel-related CO_2emissions in industrial plants (**carbon capture**) and, where applicable, the removal of carbon from the air (direct air capture, **DAC**) for industrial use (CCU) or long-term storage (CCS). In addition, **data centres** are expected to generate significant excess heat potential in the future. Although data centres are not directly related to the energy transition, they are nevertheless listed and discussed here under "new applications" due to their high relevance.

POWER-TO-X SYNTHESIS

Power-to-X (PtX) refers to the production of chemical energy carriers such as hydrogen, methanol, and other synthetic hydrocarbons using renewable electricity. Depending on the target product, different technologies and process chains are used, each with its own energy and raw material requirements. Figure 25 shows a selection of relevant synthetic fuels and industrial products and the associated value chains from raw material supply (energy, water, and CO_2), water splitting (H_2 and syngas), synthesis processes, and treatment processes. In addition to the main products**, excess heat** is generated in almost all process steps**,** with the temperature level and quantity varying greatly.

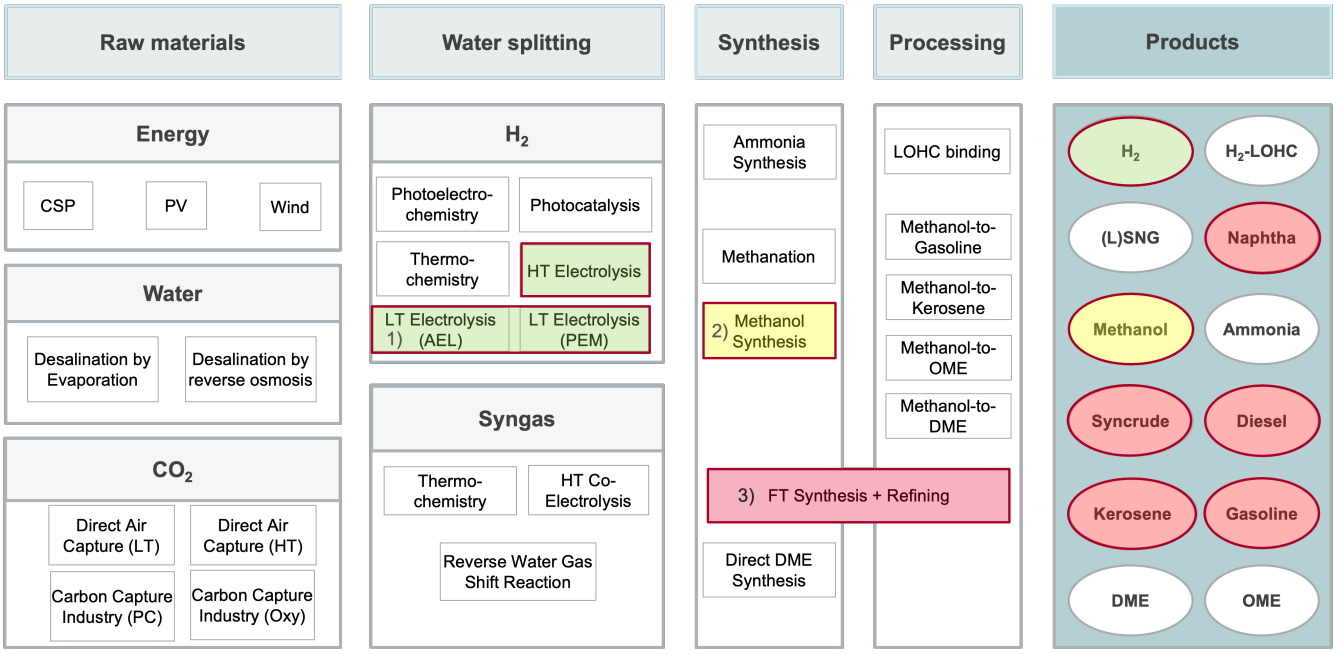


Figure 25: Selection of relevant renewable PtX products and their associated raw materials and process chains

AEL: Alkaline electrolysis
CSP: Concentrated solar power
DME: Dimethyl ether
FT: Fischer-Tropsch

LOHC: Liquefied Organic Hydrogen Carrier *(L)SNG: (Liquefied) Synthetic Natural Gas*
OME: Polyoxymethylenedimethylether *Oxy: Oxyfuel*
PEM: Polymer Electrolyte Membrane *PC: Post Combustion* *PV: Photovoltaics*

Source: (Zelt et al., 2020, 2021), own colour highlights

The following are examples of the processes highlighted in colour in Figure 25: HT and LT electrolysis (No. 1 green path), methanol synthesis (No. 2 yellow path), and Fischer-Tropsch synthesis with subsequent refining (No. 3 red path) are analysed in terms of their heat requirements and excess heat potential.

The starting point for most PtX chains is **electrolysis**. It converts water into hydrogen (H_2) and oxygen (O_2) using electrical energy. In **low-temperature electrolysis (LT electrolysis),** which is operated using alkaline electrolysis (AEL) or polymer electrolyte membrane (PEM) variants, the reaction takes place at temperatures of 50 to 90°C (Saravia & Gehrmann, 2024). The power requirement, including auxiliary equipment, is around 55 kWh per kilogram of H_2. The process is chemically endothermic; the energy is supplied entirely by electrical current. The heat generated by the electrochemical reaction and electrical resistance losses causes the cells to heat up, making continuous cooling necessary. This produces low-temperature excess heat at around 50 to 60°C (GET H2, 2024) .

High-temperature electrolysis (HT electrolysis; SOEC, solid oxide electrolysis cell) uses water vapour at around 800 to 1000°C (Dahiru et al., 2022). It requires both electrical energy (typically 42 kWh/kg H_2) and thermal energy in the form of hot water vapour (Fallisch et al., 2018). The higher the vapour temperature, the lower the electrical energy requirement. Due to the high operating temperature range, part of the heat converted in the system can be recycled; hot exhaust gas streams also provide high-quality excess heat that is suitable for steam generation or for heating downstream reactors. SOEC technology thus functions as both a heat sink and a heat source, enabling flexible coupling with other thermal processes.

Most subsequent synthesis processes require a carbon source in addition to hydrogen. The carbon (in the form of carbon dioxide CO_2) can be obtained either from industrial waste gases (see section below, ‘Carbon capture’) or by direct capture from the air (see next section below, ‘Direct air capture (DAC)’). Depending on the process, both paths require different amounts of electricity and heat. If carbon monoxide (CO) is required for the subsequent synthesis, it is usually produced via the Reverse Water Gas Shift reaction (RWGS), in which CO_2 and H_2 are converted into CO and water. This reaction is endothermic and requires a considerable amount of heat at a temperature level of around 650°C (Sternberg et al., 2017). The energy requirement for one tonne of synthesis gas is around 1.5 MWh_{el} and 0.7 kWh_{th}. However, it is also possible to substitute about a quarter of the electricity requirement with additional heat. Coupling with high-temperature excess heat from an SOEC electrolysis cell or Fischer-Tropsch synthesis is technically obvious and energetically advantageous.

Methanol synthesis, a much-discussed PtX process, combines hydrogen and CO_2 to form methanol (CH_3OH) and water. It is an exothermic process, meaning that the chemical reaction releases heat. The

reactor is operated at 200 to 300°C and 50 to 100 bar (Scholz et al., 2025). During the reaction, heat must be continuously dissipated to prevent the catalysts from overheating. This reaction heat is available at a medium temperature level and can be used either internally (e.g., for preheating reactants or for distillation) or externally (e.g., for steam generation or district heating supply to third parties). The electrical energy requirement of the synthesis itself is low and is essentially limited to compressors and auxiliary units. The methanol synthesis thus converts the previously produced hydrogen into a liquid energy carrier with low additional power consumption, generating process heat in the process.

The Fischer-Tropsch synthesis converts a mixture of hydrogen and carbon monoxide into liquid hydrocarbons (synthetic crude oil/syncrude), which can then be further processed into synthetic diesel, kerosene or naphtha. This is also a highly exothermic reaction. The reactor is operated at 170 to 360°C, depending on the desired product output and process (Boymans & Liakakou, 2018). The electrical requirements of this synthesis are also limited to auxiliary units. Similar to methanol synthesis, there are also applications for medium-temperature excess heat.

Overall, the PtX processes described are characterised by a complex interplay of electricity and heat flows, which vary greatly depending on the technology and process chain. While most electrolysis processes are electricity-dominant and only generate low-temperature excess heat, high-temperature electrolysis and exothermic syntheses are significant sources of heat. Conversely, CO_2 capture and RWGS reactions require process heat, which can be partially covered in integrated plants by internal heat recovery.

In large-scale, thermally coupled plants, efficient energy cycles can be established in this way: excess heat from synthesis and, where applicable, high-temperature processes cover the heat requirements of the upstream stages, while excess heat at medium temperature levels can be fed into industrial networks or district heating systems. Decentralised electrolysis plants at wind or PV sites usually generate only small amounts of low-temperature excess heat, the potential uses of which depend on the individual site. The extent to which a large-scale expansion of PtX technologies can make an overall positive contribution to excess heat utilisation therefore depends heavily on factors such as the choice of process and location, as well as the extent of heat integration.

Potential effects on excess heat utilisation:

- H_2 electrolysis: ↗
- Methanol synthesis: ↗
- Fischer-Tropsch synthesis: ↗

CARBON CAPTURE

CO_2 capture is a new, additional process at industrial plants that is designed to prevent CO_2 emissions into the atmosphere. The captured CO_2 can then be compressed, transported away and permanently

stored (**carbon capture and storage – CCS**) or it can be used to supply CO_2 or carbon for industrial processes (carbon capture and usage – CCU). The transport (after compression) and permanent storage of CO_2 are insignificant for excess heat utilisation.

Carbon capture and usage (CCU) requires a carbon source that is also climate-neutral in the long term for a climate-neutral energy system. Either biogenic sources, including biogenic waste (see 4.3.1.2 Switch to renewable energy sources), or carbon captured from the air (see section above, 'Direct air capture (DAC)') can be used for this purpose. The potential for purely technical applications (e.g., CO_2 as a fire extinguishing agent or in the beverage industry) is negligible. The most relevant applications in terms of quantity are seen in the synthesis of climate-neutral fuels and in basic chemicals (see section 'Power-to-X synthesis'). For information on the impact on excess heat potential, please refer to the relevant chapters on carbon *utilisation*.

The following subchapter focuses on the excess heat-relevant process step of **carbon capture** (and compression) within CCS or CCU. The choice of capture method has a significant influence on the usable or residual excess heat potential. A distinction is made between

- *Pre-combustion* technologies with separation of CO_2 from the fuel *prior* to combustion (in particular, production of so-called blue hydrogen from natural gas by steam reforming or production of synthesis gas from coal by gasification)
- *Post-combustion* technologies, which separate CO_2 from the flue gases *after* combustion by chemically (amine scrubbing, calcium looping, mineralisation) or physically (TSA/PSA, membrane and cryogenic processes[10]) binding it to a sorbent, and
- *Integrated processes* (oxyfuel, indirect calcination, integrated calcium looping) with concentration of CO_2 within the process.

Below, the two most important separation processes, oxyfuel (integrated or partially integrated) and amine scrubbing (post-combustion), are analysed using the example of the cement clinker burning process in the cement industry regarding excess heat utilisation. Cement clinker production is chosen as an example because, on the one hand, large quantities of CO_2 are generated in this process and, on the other hand, this CO_2 generation is widely considered to be unavoidable. The pre-combustion process is also briefly outlined.

The analysis is based on the "Technology Papers 2022" (ECRA, 2022) by the ECRA (European Cement Research Academy), a reference work on the available CO_2 capture processes with a comparative

[10] TSA = Temperature Swing Adsorption / PSA = Pressure Swing Adsorption / Cryogenic process = Cooling the exhaust gas stream to very low temperatures to liquefy and separate the CO_2 under pressure.

assessment based on criteria such as capture rate, technical maturity, CAPEX, OPEX, and energy requirements, as well as on the study "Climate-neutral cement region Erwitte/Geseke" (Brexel, 2024, p. 16 ff.), which examined how cement production in a real cement region with annual emissions of 2.5 million tonnes of CO_2 can be made climate-neutral.

Carbon capture: Pre-combustion

In a first step, a synthesis gas (gas mixture of H_2 and CO) can be produced from gaseous fuels (natural gas or other hydrogen-rich gases) by means of steam reforming, and from solid fuels (coal, biomass, waste) by means of gasification. In a second step, steam is used to extract further hydrogen from the synthesis gas and, at the same time, convert the carbon monoxide into carbon dioxide, which is then separated (pre-combustion carbon capture). Steam reforming and gasification (1st process stage) are both endothermic, i.e., energy-consuming processes, while the subsequent Water Gas Shift reaction (WGS, 2nd process stage) is exothermic, i.e., it releases energy. The overall energy balance and the associated question of excess heat extraction or utilisation depend to a large extent on the respective process conditions. It is therefore only possible to make statements about excess heat potential on a case-by-case basis. The pre-combustion process can only capture and separate fuel-related CO_2 emissions, not process-related emissions.

Carbon Capture: Oxyfuel (fully integrated)

In the oxyfuel process, combustion in power plants or furnaces (in this case, rotary kilns in the cement industry) takes place with pure oxygen rather than air. This means that, unlike combustion in an air atmosphere, the nitrogen in the air (around 78%) does not have to pass through the combustion process. The flue gas produced in the oxyfuel process therefore consists mainly of CO_2 and water vapour, which can be easily separated by condensation. This results in maximum capture efficiency for CO_2. The additional energy required for the oxyfuel process results in particular from the electricity-intensive supply of oxygen in an air separation plant and is estimated at 0.75 and 1 TWh for the above-mentioned example cement region[11]. In contrast, the fuel requirement for the oxyfuel process is only slightly higher, mainly due to higher heat radiation as a result of smaller cross-sections in the gas pipes and the fact that the heat from the burnt clinker cannot be used to heat the combustion oxygen in the same way as in conventional kiln systems for heating the combustion air (CI4C, 2024) . The use of the fully integrated oxyfuel process usually requires the construction of new power plants or kiln systems and correspondingly high investment volumes.

[11] Studies (Darde et al., 2009; ECRA, 2012) estimate the additional specific electricity requirement for a large-scale plant at 120 to 150 kWh per ton of CO_2. As an alternative to extracting oxygen from the ambient air, the gas can also be separated in a water electrolysis plant, whereby hydrogen is produced at the same time.

Carbon Capture: Partial oxyfuel (partially integrated) and separation of rotary kiln exhaust gases

In cement clinker production, around 75% of total CO_2 emissions are released during the process-related deacidification of the clinker raw material limestone in the calciner[12]. The remaining emissions are generated in the rotary kiln due to the fuel used. With partial oxyfuel, oxygen combustion is limited to the area of unavoidable process emissions. To this end, existing plants are retrofitted with an oxyfuel calciner. For the remaining 25% of fuel-related emissions from the rotary kiln, a separate post-combustion solution such as calcium looping or PSA/cryogenic process must then be found. Calcium looping also requires the use of a carbonator[13], and the fuel-related primary energy requirement per tonne of clinker increases by 60-70%. This additional energy requirement can be covered, at least in part, by existing unused excess heat potential, which is then no longer available for external use. The combined PSA/cryogenic process is not as heat-intensive and therefore hardly reduces the existing excess heat potential. However, the process has an electricity consumption of approx. 450 kWh/t CO_2, which is almost twice as high as that of the oxyfuel/cryogenic process.

Carbon Capture: Amin washing

Amin washing is a post-combustion process in which CO_2 is filtered out of the exhaust gas stream in existing plants by adding washing units downstream of the combustion process using thermochemical methods. The high additional heat requirement for desorption in amine scrubbing can only be partially covered by heat recovery, and even then, only by interfering with the existing plant structures.

For the central separation of an aggregate CO_2 volume of 2.5 million tonnes per year, approximately 6 tonnes of steam per minute would be required in an exemplary cement region. The energy requirement of the desorber, at approximately 2.6 TWh/a, is therefore similar to the thermal energy requirement of the clinker burning process itself (approximately 3.17 TWh/a)[14]. In a CCS pilot project in Brevik, Norway, approximately 50% of the heat required for amine scrubbing was covered by integrated heat recovery. Approximately two-thirds of the recovered heat comes from the clinker burning process, with another third coming from the end-of-pipe process of CO_2 capture and liquefaction itself. This means that for the cement region cited as an example, (previously unused) excess heat at a temperature level above 120°C in the order of 1.3 TWh would no longer be available for other purposes. In addition, a further approx. 1.3 TWh of additional heat would be required for desorption. Theoretically, this heat can be

[12] At temperatures of approx. 850°C to 950°C, the calciner breaks down calcium carbonate ($CaCO_3$) into calcium oxide (CaO) and carbon dioxide (CO_2).

[13] The carbonator absorbs carbon dioxide (CO_2) and reacts it with calcium oxide (CaO) at temperatures of approx. 650°C to form calcium carbonate ($CaCO_3$).

[14] This calculation is based on a thermal energy requirement of 3 352 MJ (931 kWh) per ton of cement clinker.

recovered from other low-temperature sources within the process (30 to 120°C) using multi-stage high-temperature heat pumps, which would then also no longer be available for external extraction.

Potential effects on excess heat utilisation:

- Pre-combustion: ➔
- Oxyfuel: ➔
- Partial oxyfuel: ➘
- Amin washing: 🡻

DIRECT AIR CAPTURE (DAC)

To offset unavoidable GHG emissions, e.g., from agriculture, it is necessary to compensate for remaining emissions to achieve long-term climate neutrality. Since 2009, the direct capture of CO_2 from the air (Direct Air Capture, DAC) with subsequent storage (Direct Air Capture and Carbon Storage, DACCS) has been developed as a technical option for this compensation (Fasihi et al., 2019). Various processes are being tested (absorption, adsorption, electrochemical, membrane, etc.), with some processes still in the early stages of development and none yet having reached a Technology Readiness Level (TRL) close to market maturity.

The most advanced processes are absorption and adsorption, both of which are very energy intensive. Heat demand dominates over electricity demand, accounting for up to 85% of total energy demand (Block et al., 2024; Postweiler et al., 2024). The exact figures depend on various factors such as the sorption medium and environmental conditions (Deutz & Bardow, 2021; Wenzel et al., 2025) .

The *adsorption process (low temperature, LT)* operates at a temperature level of 80 to 120°C and, according to current literature, currently has a heat requirement of 1500 to 3000 kWh per tonne of CO_2 (median 1944 kWh/t CO_2). This is expected to be reduced to 1100 to 1500 kWh/t CO_2 (median 1257 kWh/t CO_2) by 2040 (Wenzel et al., 2025). To meet heating requirements in a climate-neutral manner at the specified temperature level, high-temperature heat pumps (using LT excess heat), solar or geothermal heat, and the direct use of industrial excess heat (above approx. 120°C) are all possible options. The excess heat used would then no longer be available for other purposes, such as feeding into heating networks. Due to the modular design of the adsorption units (as practised by Climeworks, for example), switching individual modules on and off allows for relatively flexible operation of the DAC plant. This makes it possible to respond to fluctuating heat flows. However, due to the high CAPEX of adsorption DAC technology, high full-load hours are required for economical operation.

The *absorption process (high temperature, HT)* operates at temperatures of around 900°C and, according to current literature, currently has a heat requirement of 1600 to 2800 kWh/t CO_2 (Ozkan, 2025). Due to the high temperature level, the use of excess heat is generally not possible here, and separate (climate-neutral) high-temperature heat sources would have to be found or constructed.

Conversely, excess heat recovery from the process is theoretically conceivable, but more detailed investigation would be required to determine what amounts of energy could be extracted at what temperatures in the complex plant design.

Potential effects on excess heat utilisation:

- Adsorption process (LT): ↘
- Absorption process (HT): ➔

DATA CENTRES

More powerful digital services such as Industry 4.0, autonomous driving, machine learning, artificial intelligence (AI), social networking, video streaming, etc. require ever more computing power in ever more data centres. Data centres convert almost 100% of the electrical energy they consume into thermal energy, which must be cooled away. This excess heat is reliable and available all year round, as data centres typically operate 24 hours a day, seven days a week. This makes excess heat from data centres particularly interesting for applications that require heat all year round, such as swimming pools, hospitals, laundries, or greenhouses (including new applications such as vertical farming). IEA projections indicate that global electricity consumption by data centres alone will more than double from around 400 TWh to around 950 TWh between 2024 and 2030 (Figure 26). The main drivers are the United States and China (Table 7, left-hand side) by region, and accelerated servers with high computing power for demanding tasks (Table 7, right-hand side) by equipment features.

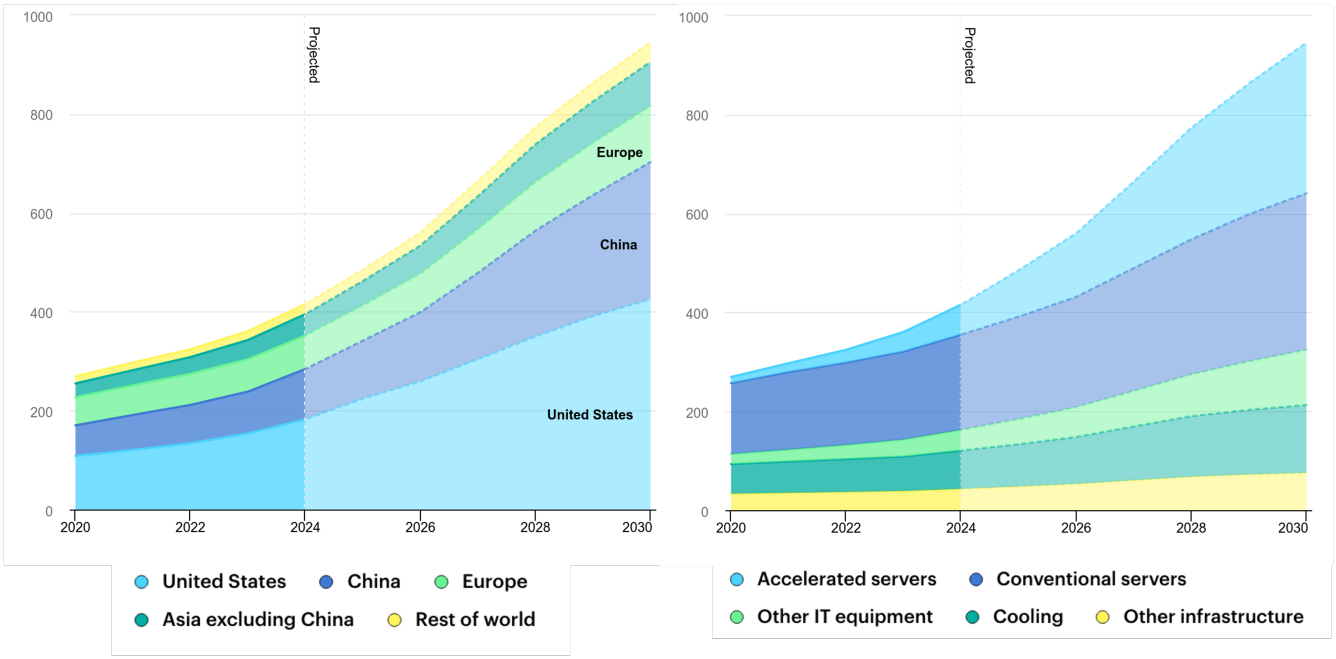


Figure 26: Historical and projected global electricity consumption of data centres in terawatt hours (TWh) in the baseline scenario, broken down by region (left) and equipment features (right)

Source: IEA (2025), Energy and AI, IEA, Paris https://www.iea.org/reports/energy-and-ai, Licence: CC BY 4.0

In some regions and countries, such as Europe (EU Energy Efficiency Directive (EED), 2023) or Germany (Energieeffizienzgesetz (EnEfG), 2023), there are already rules in place for the mandatory and gradual increase in the use of excess heat from data centres. (DENEFF, IWN und IER, 2023) provides an overview of 99 best practice examples of implemented excess heat projects from 15 countries in Europe, North America, and Asia.

The white paper by NeRZ (Network for Energy-Efficient Data Centres) and eco (Association of the Internet Industry) provides a catalogue of technical application possibilities (NeRZ und eco, 2019). According to this, cooling systems can be divided according to temperature level and cooling technology or cooling medium into:

- Air cooling (recirculating air conditioners with cold water coils (< 30°C)
- Water or liquid cooling (Direct Liquid Cooling DLC, approx. 30°C - 60°C).

To make heat from **air-cooled data centres** with relatively low temperatures usable for conventional heating systems, heat pumps are usually required. Technical innovations such as closed-loop systems, in which heat exchangers are installed in both the warm and cold air flows and connected to each other via a brine pipe, enable particularly efficient and flexible cooling and heat extraction for air-cooled data centres.

In modern approaches to **water-cooled IT systems** at higher temperature levels, the cooling medium water (or special cooling fluids) improves the efficiency of heat recovery and facilitates connection to heating and district heating networks. In addition, energy consumption and costs for cooling are reduced, as operation at higher flow temperatures (in the cooling circuit) is possible, thereby reducing the amount of cooling required by compressors.

With water cooling, some of the excess heat generated can also be used *internally* for cooling with the aid of adsorption or absorption chillers. The example of a reference plant[15] shows that this can reduce the power required for cooling by a factor of approximately 10 compared to a compression chiller. Overall, this results in approximately 15% less excess heat. However, if excess heat is also used with the aid of sorption machines to provide *external* cooling to third parties, in the overall balance and in relation to the total excess heat of the reference plant, 68% *additional excess heat* and 55% *additional cooling capacity* are generated. This means that internal use for cooling generation by means of sorption

[15]Reference system based on the HotFIAd concept (NeRZ und eco, 2019, p. 8 ff.): IT (server, network, storage): 23 kW_{el}, compression chiller: 5 kW_{el}, other consumers (UPS losses, lighting, fire protection, etc.): 3 kW_{el}; total power consumption: 31 kW_{el}; Excess heat reduction for *internal* use in cooling using adsorption chiller (0.5 kW_{el}): (31 – 26.5) / 31 = 15%; Additional cooling capacity for *external* cooling supply using adsorption chiller (1 kW_{el}): 17/31 = 55 %; Additional excess heat with *external* cooling supply (52-31)/31 = 68%.

systems slightly reduces the excess heat potential, whereas external use (in the form of cooling supply) significantly increases it again. However, as Figure 26 (right-hand side) shows, regardless of this, the greatest energy demand—and thus also the greatest excess heat potential—does not come from cooling, but from the actual server and IT infrastructure, and this trend is set to increase in the future.

The increasing IT density and computing power and the associated need for liquid cooling (on the side of the heat source), as well as the expansion of 4th and 5th generation low-temperature heating networks (on the side of the heat sink), are factors that could significantly improve the technical and economic potential of excess heat projects in the coming years.

Potential effects on (external) excess heat utilisation:

- New and more powerful data centres, including new high-temperature cooling technologies: ↑

4.4 CONCEPTS FOR INDUSTRIAL HEAT INTEGRATION INTO DISTRICT HEATING

In 3rd and 4th generation district heating networks, decentralized heat sources such as industrial excess heat are used in addition to heat generators from the energy supply company. 3rd generational networks typically operate between 70-100°C, whereas 4th generational networks use even lower temperatures of under 70°C. By integrating mostly low-emission heat, conventional heat generators can be replaced, and emissions from district heating networks reduced [Bran 2014]. The following requirements must be met:

- The heat supplied must exceed the temperature level of the district heating network either directly or using heat pumps.
- The timing of heat demand and excess heat must be balanced, and heat storage systems may need to be used.
- The spatial proximity and temperature level determine the quantity and type of piping required for the district heating connection.

Furthermore, the energy supply company must comply with legal requirements, e.g., regarding pricing or emissions from the heat supplied, and ensure security of supply. Particularly in cases of uncertainty regarding the excess heat source, e.g., whether an industrial process chain will continue to operate, appropriate redundancies must be maintained in the heat generation of the energy supply companies [Stark 2021].

When planning a district heating connection for decentralized heat sources such as industrial surplus (excess) heat, a distinction must be made between different stages. First, the decentralized heat source must be connected, i.e., the surplus (excess) heat must be transferred to a heat transfer medium in a heating network. In the next step, the heat is transported via heating networks to the boundary of the industrial site. At the boundary, the heat is transferred to the energy supply company via a heat transfer station and finally transported to the district heating network. There, the heat is integrated and transported via the existing district heating network to the heat consumer and transferred. Investments in various system components such as heating networks, heat exchangers, heat pumps, or heat storage tanks may be necessary in the various sections; the corresponding operating parameters must be considered in the planning. For industrial companies, the system components and operating parameters up to and at the heat transfer station must be integrated into the planning [Stark 2021, Fang 2015].

The following sections describe the techno-economic framework conditions and principles for connecting decentralized excess heat sources. They also describe innovative approaches for complex heat transfer stations and holistic approaches to integrating industry and district heating.

4.4.1 CHARACTERIZATION OF INDUSTRIAL HEAT POTENTIAL

This section adapts the AGFW guide to tapping excess heat sources for district heating supply (with permission by the AGFW), along with supplementary resources [Stark 2021].

With regards to connecting industrial excess heat to district heating networks, successful integration is influenced by industrial suppliers' sectors. While this chapter focuses on technical potential found in industrial excess heat based on its source, the following list briefly addresses further considerations from the perspective of suppliers:

- High investment costs for retrofitting established heat networks need to be considered, especially when aiming to use excess heat at a different location than where it is generated [Stark 2021]
- Excess heat uptake by the grid operator must be ensured from both a financial and technical perspective, potentially limiting integration into district heating grids [Kohne 2023]
- Excess heat utilization (internal and external) can be used to achieve ISO 14001 certification [ISO 2026]
- Coupling excess heat utilization with an energy management system can result in up to 10% reduced energy costs in energy-intensive companies [Stark 2021, ISO 2018]

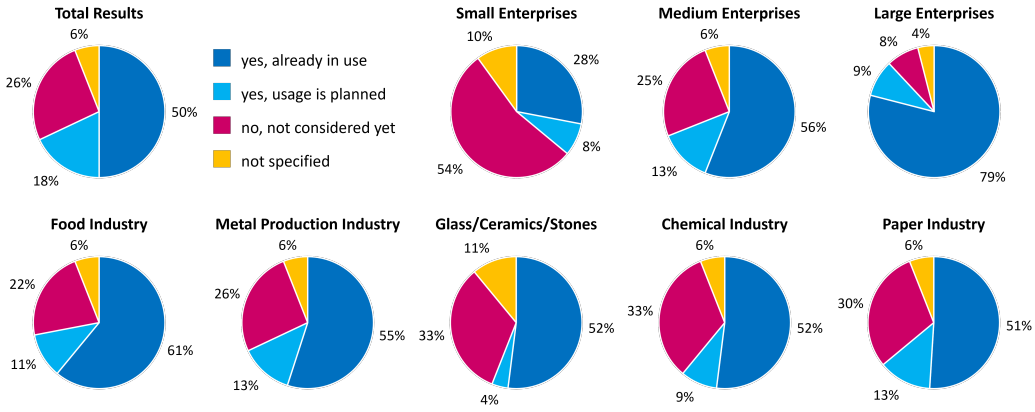


Figure 27. Survey results for the question "Does your company already use or plan to use excess heat?", adapted from [BMWE 2024]

Excess heat utilization is not yet an industrial standard. An investigation carried out by Fraunhofer IPM and IfD Allensbach found that the less than half of the surveyed German companies were using their excess heat or had plans to use it as of 2018, see Figure 27. The survey also showed that excess heat utilization scaled with company size, with smaller companies having yet to address the topic. Industrial sectors had only minor impacts on

whether excess heat was utilized; the food industry led with a reported 61% utilization, compared to the metal production industry's 55%, the glass/ceramics/stones and chemical industries' 52%, and the paper industry's 51%. [BMWE 2024]

Reasons for the lack of extensive excess heat utilization could either be traced back to financial or technical hurdles. Of the companies that reportedly lacked excess heat utilization, almost half believed that there was not sufficient potential for it on their premises. At the same time, only 14% of all companies surveyed tracked the amount of excess heat generated in their facilities on a yearly basis. As for financial hurdles, one metal producing company reported that although they were willing to export their excess heat, there was no local demand for it.

4.4.2 QUALITATIVE FEATURES OF EXCESS HEAT

The District Heating Working Group (AGFW) distinguishes between two types of excess heat utilization in their excess heat guidelines: **internal and external** [Stark 2021]. Internal excess heat utilization aims to recycle waste by integrating it into the source process (heat recovery) or into other on-site operational processes, which can lead to higher process efficiencies due to lower thermal inputs. External excess heat utilization can further be split into two aims. The first is to directly supply excess heat to a neighbouring site with demand for steam, district heating or cooling, or electricity. This option creates dependencies between the supplier and consumer(s), both in terms of financial returns on the investment for both parties, as well as technical operations for the consuming party. Both options need a matching of sources and sinks, see Figure 28: Favourable conditions for source-sink-matching of excess heat, Source: Wuppertal Institute and DLR (2015). The second aim of external excess heat utilization can be to feed excess heat into a pre-existing heating network, e.g., for district heating.

One can further distinguish between **direct and indirect usage** of excess heat. In this context, indirect usage refers to processes where the temperature level of the excess heat is altered, e.g., using electrified heat pumps to raise the temperature level.

An important distinction can be made between **medium-bound and diffuse** excess heat. Medium-bound heat, in which the heat is stored in a carrier medium, can be utilized more easily with purpose, in contrast to diffuse excess heat, which is often emitted uncontrolled into the environment and can thus be difficult to capture and use effectively [Hirzel 2013].

The **carrier medium** is typically either gaseous (e.g., flue gas, steam, vapor) or liquid (e.g., water, water with additives, thermal oils). It influences the type of heat exchangers that need to be installed, with mediums with higher heat capacity and heat transfer requiring smaller heat exchangers.

Reliability of the supply of excess heat needs to be considered by both parties in the case of external excess heat utilization. It can affect production schedules and, in case of insufficient

thermal energy on the receiving party's side, increase energy costs due to additional purchases.

	Waste Heat Source	Heat sink	Favourable conditions
Heat quantity	Heat supply	Heat demand	Demand = Supply
Temperature	Available temperature level	Required temperature level	Available temperature > Required temperature
Time	Temporal progression of heat supply, cycles, downtime, idle time	Temporal progression of heat demand, cycles, downtime, idle time	Matching time curves
Location	Location of heat supply	Location of heat demand	Short distance
Medium	Medium of waste heat flow (water, steam, air, flue gas, vapours, oil); properties: density, specific heat capacity	Suitable media for heat supply	Waste heat medium suitable for conversion or storage
Pressure level	Pressure level of the waste heat flow	Suitable pressure level for heat supply	Matching pressure levels
Mass flow and volume flow	Mass flow before heat conversion		High mass flow
Toxicity	Toxicity of the waste heat flow, Limit values	Tolerance of the heat sink to toxicity	No toxicity in the waste heat flow
Abrasiveness	Abrasiveness of the waste heat flow	Tolerance of the heat sink to abrasiveness	No abrasiveness in the waste heat flow

Figure 28: Favourable conditions for source-sink-matching of excess heat, Source: Wuppertal Institute and DLR (2015)

4.4.3 QUANTITATIVE FEATURES OF EXCESS HEAT

When it comes to quantifying costs for excess heat integration, the AGFW distinguishes between **generation and development costs** [Stark 2021]. Generation costs refer to the costs required to extract the excess heat from its source process, while development costs refer to costs required for the infrastructure and transportation of the extracted excess heat to a subsequent process or heat transfer station.

As per the AGFW and Fraunhofer ISI, the **temperature level** of excess heat is a defining characteristic of excess heat [Stark 2021, ISI]. Temperature levels directly affect the potential usage of excess heat, as insufficient temperatures may require raising (or lowering) through additional technologies. The following distinctions can be made in accordance with Schaefer [Schaefer 1995]:

- Low-temperature excess heat: below 150°C
- Medium-temperature excess heat: between 150°C to 500°C
- High-temperature excess heat: above 500°C

The **quantity of excess heat** at a specific temperature level is likewise closely linked to potential usability. With higher quantities, the profitability of excess heat utilization increases [Kohne et al. 2023].

Spatial proximity describes the distance of the excess heat source to a potential excess heat sink. Closer proximity decreases both costs of excess heat transportation (building, operating, and maintaining the necessary infrastructure) as well as transportation losses (heat dissipation). In the case of connecting to an existing nearby district heating network, the dependence on finding individual heat sinks is reduced.

Availability of excess heat defines how much excess heat is available per time frame, i.e., per day, week, month, quarter, season, or year. For example, an excess heat supplier may choose to utilize their excess heat internally in winter to reduce their building heating demand, while they may have greater quantities of excess heat for external utilization during summer, due to excess heat from cooling processes. Closely matching supply and demand for excess heat increases profitability of excess heat utilization.

4.4.4 POTENTIALS BASED ON ORIGIN

Using the features presented in the previous sections, initial classifications for excess heat can be made based on the point of origin. To this end, this section considers three different origins: the industrial sector, the service sector, and data centres. Together, they result in large, untapped potential for excess heat utilization. A technical study conducted in the German federal state of North Rhine-Westphalia concluded that on a federal state level, the potential lies between 44-48 TWh/a [Reckzügel 2019]

The multitude of processes and machines used in the **industrial sector** result in a heterogenous profile for excess heat utilization. For example, while cleaning processes typically result in excess heat at a temperature level of about 60°C, processes used in raw material industries result in excess heat temperature levels that often exceed 1000°C [Stark 2021]. **Ovens** commonly represent the largest source for excess heat in companies [Flum 2019]. At the same time, about 60% of the energy inputs in ovens are lost without proper excess heat utilization [Flamme 2000]. Table 9 gives an overview over representative exhaust gas temperatures found in different ovens:

Table 9: Exhaust gas temperatures for ovens from different branches of the industrial sector, adapted from [Stark 2021]

Type of Oven	Further Specifications	Typical Exhaust Gas Temperatures
Ceramics Kilns		150°C - 1000°C
Blast Furnace		200°C - 400°C

Cement Kilns		400°C - 600°C
Melting Furnace	Open-Hearth Furnace Glass Furnace with Regenerator Glass Furnace without Regenerator	400°C - 700°C 600°C - 800°C 900°C - 1300°C
Annealing Furnaces		600°C - 700°C
Heating Furnace	Glass Furnace with Regenerator Furnace without Regenerator	300°C - 600°C 700°C - 1200°C

Temperature levels found in the **service sector** are typically lower than in the industrial sector. Nonetheless, they can account for over 14% of the energy demand for heating. Therefore, companies in the service sector can aim for internal excess heat utilization to lower their energy costs, or external excess heat utilization by integrating their excess heat into municipal heating networks. However, excess heat from the service sector has higher seasonal fluctuations, as it commonly is sourced from cooling applications, which have heavier usage during the summer months [Stark 2021]. Table 10 gives an overview of representative exhaust gas temperatures found in different service sector branches:

Table 10: Typical excess heat features for different branches of the service sector, adapted with permission from AGFW [Stark 2021]

Branch	Medium	Temperature Level	Power Range	Availability
Treatment Plants	Residual Heat from Digester Gas Combustion Outlet Heating Water	~100°C 8°C - 20°C	100 kW - 500 kW 500 kW – 2 MW	residual heat during summer (internal utilization during winter), outlet water all year round with seasonal fluctuations
Laundries	Wastewater Exhaust Air	20°C - 60°C 20°C - 40°C	< 100 kW < 100 kW	1-shift operation, all year round
Retail	Cooling Water Exhaust Air	30°C - 40°C 5°C - 30°C	100 kW - 500 kW 100 kW - 500 kW	higher potential during summer

				and based on opening hours
Hospitals	Cooling Water Wastewater Exhaust Air	30°C - 40°C 10°C - 20°C 5°C - 30°C	100 kW - 1MW 100 kW - 1MW 100 kW - 1MW	wastewater and exhaust air all year round, cooling water during heating period
Cold Stores	Cooling Water	30°C - 40°C	100 kW - 10 MW	higher potential during summer
Commercial Kitchens	Wastewater	20°C - 30°C	< 100 kW	based on opening hours
Swimming Pools	Wastewater Exhaust Air	15°C - 20°C 10°C - 25°C	100 kW - 500 kW 100 kW - 500 kW	higher potential during winter and based on opening hours

Data centres serve as a continuous source of excess heat due to being operational all year round, which make up around 3% of the global energy demand [Yuan 2023]. At the same time, they hold a high potential for excess heat utilization, as up to 70% of the excess heat can be recovered using large heat pumps [Stark 2021]. At the same time, only 19% of data centres reportedly utilize any form of their excess heat [Stark 2021]. Excess heating generated in data centres is a byproduct of a data centre's electricity usage. Thus, greenhouse gas emissions for excess heat are directly linked to the electricity mix used by the data centre, with higher shares of renewable energies in the mix contributing to reducing greenhouse gas emissions [Zäh 2024].

Table 11: Typical excess heat features for data centres, adapted from [Stark 2021, Yuan 2023]

Branch	Medium	Temperature Level	Power Range	Availability
Data centres	Cooling Liquids Air-to-Liquid Cooling Air-Side Cooling	20°C - 60°C 20°C – 30°C 15°C – 50°C	1 MW - 10 MW	all mediums continuous, all year round (with air-side cooling having an increased potential during summer)

IDENTIFYING EXCESS HEAT POTENTIALS WITHIN COMPANIES

For maximizing the potential of internal utilization of excess heat sources, it is important that companies start by auditing their heat supply systems to identify opportunities for reducing their temperature requirements. To this end, a bottom-up approach is recommended. During the auditing process, companies should identify potential energy savings and create long-term heating plans, to ensure that future infrastructure for distributing excess heat is properly dimensioned for long term usage.

An optimization of internal heat flows may result in lower amounts of excess heat for external utilization, to the point that supplying excess heat to heating networks or nearby companies may exceed potential profits. In this case, internal utilization should be considered.

The benefits of excess heat utilization for companies are:

- Utilizing excess heat achieves energy savings, lowers operational energy costs, reduces CO_2-equivalent emissions and by extension costs for emissions, and thus improves competitiveness.
- Profits can be made from feeding excess heat into external heat sinks, like heating networks.
- Higher compatibility with global climate goals, due to environmental conservation, as excess heat is not released into the environment.

4.4.5 CONCEPTS FOR INDUSTRIAL EXCESS HEAT INTEGRATION INTO DHC

To connect complex industrial energy systems to district heating networks in a thermo-hydraulic way, various concepts are modelled, simulated, and technically tested in application-oriented research. Some of these research approaches are outlined below.

APPROACH 1: OPTIMIZATION FOR INVESTMENT AND OPERATIONAL PLANNING OF DH CONNECTIONS

This research is a translated adaptation of the summary (chapter 5.1) in Kohne (2023) with the permission of the author, Thomas Kohne.

This section outlines systematic approaches, based on optimization methodologies for investment and operational planning of DH connections of InES.

The complexity of multi-modal industrial energy systems with cascaded thermal energy networks and excess heat potentials must be considered in investment and deployment planning. The planning of a district heating connection needs to be carried out against the

background of the energy policy objectives of security of supply, economic efficiency, and environmental compatibility, and is subject to the planning procedures and objectives of industrial energy systems, the structural change of district heating networks as well as economic and ecological framework conditions. In particular, the multi-criteria objectives of industrial companies and energy supply companies, the consideration of transformation scenarios and the consideration of different participation models must be integrated into the planning of a district heating connection.

Mathematical optimization can be used to support planning processes with quantitative models and methods, thereby facilitating and improving decisions. In the context of operations research, it makes it possible to map general investment and deployment planning to problem-specific aspects. Outside of the work of Kohne, there is no optimization methodology that maps the complexity of industrial energy systems and their planning perspective against the background of the integration of two complex systems.

Kohne presents three central models for mathematical optimization, as can be seen in Figure 29. The tripartite division of the models of the optimization methodology serves to identify objectives and possible courses of action, formalize the mathematical model as well as data acquisition, solution finding, and evaluation in the sense of operations research:

- The **descriptive model** shows the holistic view of the energy systems—industrial energy system with district heating connection and district heating network—and thus the breakdown of the investment planning of the district heating connection and the operational planning of the overall systems. The industrial energy system is described as a multi-modal energy system with cascaded thermal energy networks and a concept for a bidirectional district heating connection is drawn up. The objective is defined in terms of net present value and other target variables such as emissions and security of supply are economized or defined as framework conditions. Furthermore, the integration of transformation scenarios and participation models is derived. Semantics were also presented to illustrate the energy systems.
- The **optimization model** formalizes the descriptive model as a modular MILP model consisting of various system components of the energy systems. The individual system components can be put together individually for specific use cases. For this purpose, the optimization model consists of the basic models of operational planning and investment planning as well as the model extensions of the transformation scenarios and participation models. Overall, the optimization model integrates various aspects such as partial load behaviour, temperatures and the separation of operational and investment planning and uses mathematical methods such as regret optimization and bilevel optimization.
- The **procedure model** defines seven steps to use the optimization model against the background of the descriptive model to support concept planning. After initial

preparation, the systems are configured into a data model during data procurement (system structure of the industrial energy system and determination of variants for the district heating connection) and the data is processed in the data model and aggregated as representative periods. The solution for the application or investigation of the methodology is then defined. Finally, the solution is evaluated by analysing the results with defined key figures so that a recommendation for action can be made by means of visualization before further steps are initiated.

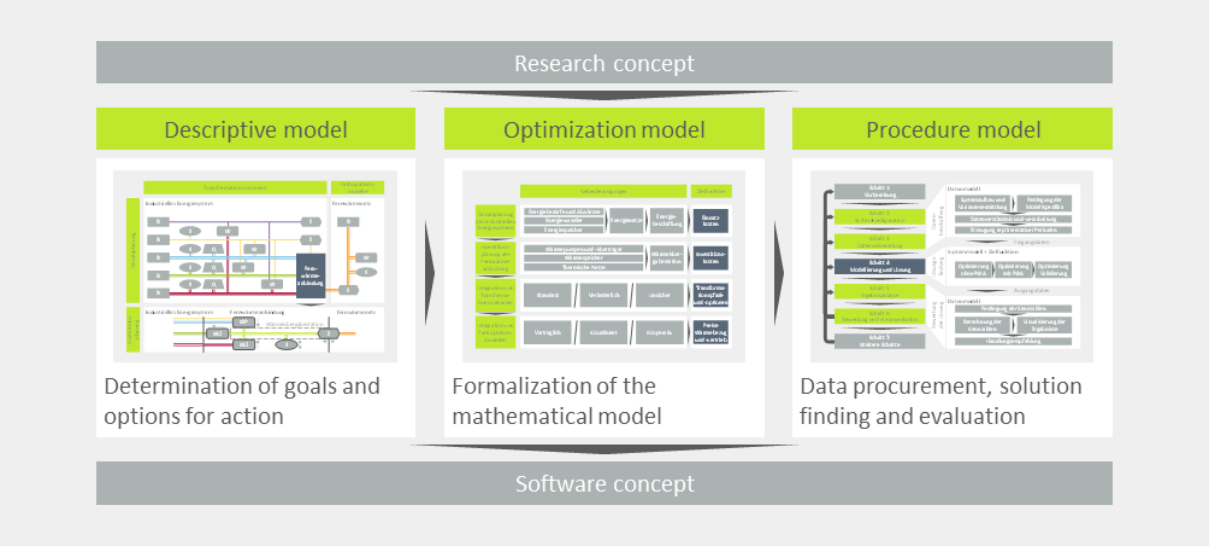


Figure 29. Models of the optimization methodology (Kohne 2023).

The qualitative and quantitative developments in the three models of the optimization methodology significantly support the concept phase for planning a district heating connection. To this end, it has been implemented as a prototype using the Python programming language, wherein requirements and an initial concept for utilization have been outlined. A test use case has been completed using the ETA Factory, a large-scale demonstrator for metalworking situated at the Technical University of Darmstadt. The results of the model and method tests show that the distribution of excess heat via a district heating connection, particularly coming from heat treatment furnaces, is economically and ecologically advantageous. At the same time, different models lead to divergent investment decisions.

The mathematical optimization methodology has been tested for industrial application with a use case in the Living Lab DELTA. The investigation regarding potentials of connecting large industrial companies to a district heating network operated by a local energy utilities company shows promising returns. This is particularly so when planning around complex transformations of industrial sites, which benefits from having several transformation options being modelled to support the planning of the district heating connection. The results of the industrial application show that a district heating connection makes economic and ecological sense even under uncertainty, and by integrating the existing uncertainty. The investment

decisions in the application case integrate a district heating connection with a heat pump so that excess heat from cooling processes can be fed into the district heating network. Nevertheless, additional parameters, e.g., desired payback periods for the industrial company and long-term supply safety for the district heating operator, need to be considered in addition to the outcome of this optimization methodology. Due to the large investments required from one (or both) parties, an agreement must be reached that satisfies these parameters, making it more beneficial for companies that lack the means of significantly reducing their on-site excess heat.

APPROACH 2: STRATEGIES TO INTEGRATE WWTPS INTO DISTRICT HEATING SYSTEMS

As cities seek to decarbonize and improve energy efficiency, tapping into unconventional renewable heat sources becomes increasingly important. Wastewater treatment plants (WWTPs) present an underutilized but promising opportunity in this regard. Given that municipal wastewater retains a significant amount of thermal energy—even after treatment—it can serve as a valuable source of low-grade heat. Integrating heat pumps at WWTPs into district heating networks is one of the key pathways to leveraging this potential. One example for this type of integration can be found in the best practices listed in Chapter 2.3 as well as in the Euroheat & Power Knowledge hub: the wastewater treatment plant in Gleisdorf, Austria.

Several studies provide comprehensive overviews of heat pump systems utilizing wastewater. For instance, Hepbasli et al. (2014) and Culha et al. (2015) outline various technical configurations and applications. Hepbasli et al. (2014) estimate that approximately 500 such systems were already operational globally at the time of their writing ten years ago. The technical and environmental potential of heat recovery from wastewater systems has been assessed in multiple national contexts. Studies from Austria (Neugebauer et al., 2015; Kretschmer et al., 2016), Hungary (Somogyi et al., 2018), the Netherlands (Frijns et al., 2013), and China (Chae & Kang, 2013) underscore the feasibility and benefits of implementing wastewater-sourced heat pumps in diverse urban environments. In Austria, Neugebauer et al. (2015) specifically evaluated the viability of integrating heat pumps at WWTPs into urban heating systems. Their analysis found that such systems could potentially reduce the Austrian greenhouse gas emissions from space heating by up to 17%, depending on the proximity of WWTPs to densely populated areas.

Operational experience also supports the viability of large-scale sewage-sourced heat pumps. Averfalk et al. (2017) review the deployment of systems installed in Sweden during the 1980s, noting that approximately 1,200 MW of thermal capacity was installed, much of it using sewage water. Although initially driven by an electricity surplus from nuclear power, these systems now contribute to grid stabilization in response to increased variability from renewable energy sources. More recently, Terreros et al. (2020) explored the role of heat pumps in rural Austrian

district heating networks. Their study concluded that using sewage water as a heat source could lower heat generation costs by 27.5% compared to biomass-based systems, further supporting the economic case for wastewater heat utilization.

As for a more far-reaching study covering the entire EU27, Mathiesen et al. (2023) estimated an excess heat potential from sewage water at 442 TWh/year for the year 2050. Wastewater heat could therefore provide a significant contribution of up to 55% of the DH demand in countries with lower overall heat demand and low industrial excess heat levels. (Mathiesen et al., 2023)

Post-treatment sewage water at WWTP carries a relatively stable temperature (typically between 8-15°C), even in winter, making it a reliable and predictable heat source (Persson et al., 2020). Additionally, the integration of WWTPs into urban energy systems aligns with the broader goals of energy sector coupling and circular economy strategies (Gruber-Glatzl et al., 2020).

The paper *"From the Wastewater Treatment Plant to the Turnstiles of Urban Water and District Heating Networks"* (Gruber-Glatzl et al., 2020) examines such integration in depth using the Gleisdorf WWTP in Austria as a case study. It demonstrates how WWTPs can evolve from isolated infrastructure into multifunctional energy hubs by using technologies like heat pumps and biogas CHP units to supply both internal and external energy demands.

A key focus of the study is the use of heat pumps to recover thermal energy from treated effluent. This recovered heat can then be used to:

- Cover internal thermal demand (e.g., sludge digestion, building heating),
- Feed into nearby district heating networks,
- Or serve both simultaneously.

To assess this, the authors model three distinct **Heat Pump Integration Options (HP-IOs)** that explore different configurations for connecting WWTPs to district heating.

HP-IO 1 – Internal Supply Focus

- **Function:** The heat pump exclusively serves WWTPs internal heat requirements.
- **Flow Temperature:** Operates at low temperature (around 35–45°C), suitable for digestion and internal heating.
- **Advantages:**
    - Technically simple and cost-effective.
    - Avoids heat losses associated with transport to external networks.
- **Limitations:**
    - Limited impact on the wider energy system.

- Underutilizes the full heat potential of wastewater.

HP-IO 2 – Direct Feed into District Heating

- **Function:** Heat from the treated effluent is upgraded via a heat pump and injected directly into the district heating network.
- **Flow Temperature:** Requires high output temperatures (70–90°C) to match district heating system needs.
- **Advantages:**
  - Maximizes external heat utilization.
  - Supports decarbonization of district heating infrastructure.
- **Limitations:**
  - Requires a high temperature lift, reducing system efficiency (COP).
  - Higher investment cost for heat pump and piping infrastructure.

HP-IO 3 – Hybrid Supply

- **Function:** Heat pump covers both internal WWTP needs and external district heating supply.
- **Flow Temperature:** Adjusted flexibly depending on demand patterns and system configuration.
- **Advantages:**
  - Offers operational flexibility.
  - Allows optimization for cost, efficiency, and emissions.
- **Limitations:**
  - Increased system complexity.
  - Demands advanced control systems for balancing internal and external needs.

For this guidebook, specifically HP-IO 2 and HP-IO 3 are of interest for connecting WWTP with DH networks. Integrating heat pumps at WWTPs can significantly strengthen DH networks by:

- Diversifying renewable heat sources,
- Stabilizing supply through baseload coverage,
- Reducing reliance on fossil fuels,
- Enhancing synergies between water and energy infrastructures.

Such integration also aligns with EU policy goals such as those outlined in the REPowerEU plan and the Energy Efficiency Directive, which encourage the use of excess heat in district heating systems. The study by Gruber-Glatzl et al. (2020) highlights that WWTPs, when equipped with heat pumps and integrated into district heating systems, can act as “turnstiles” that interlink multiple urban energy flows. Among the three HP-IOs, the hybrid model (HP-IO

3) generally provides the highest value due to its flexibility and broader system impact. However, the most suitable configuration ultimately depends on local conditions, including heat demand, temperature requirements, and infrastructure compatibility.

APPROACH 3: TECHNICAL APPROACH TO CONNECT INDUSTRY EXCESS HEAT TO DISTRICT HEATING

Integration of excess heat into heating networks

One of the challenges in utilizing industrial excess heat lies in the differing business objectives of excess heat owners and heat users.

For **excess heat owners**—industries—collecting and utilizing excess heat typically falls outside their core business activities. Excess heat is an unavoidable byproduct of production processes, which often involve a wide range of operations with intermittent schedules. Consequently, industries tend to prioritize the most cost-efficient cooling solutions, often opting for cooling methods tailored to individual production processes. These decentralized cooling systems can be more cost-effective than central cooling solutions since they only need to provide the cooling temperature required for each specific process. In contrast, a central cooling system requires a distribution network and must meet the cooling temperature demands of the most temperature demanding process.

Moreover, industrial companies focus on manufacturing and selling products or services, which are significantly more valuable than their excess heat. As a result, they often lack the motivation, expertise, and business models necessary to make their excess heat available to potential users, such as district heating companies. Additionally, because industrial production processes and business models are typically closely guarded trade secrets, there is a natural distrust of third parties becoming involved in internal processes.

For **heat users**, such as district heating utilities, the priority is to secure stable, reliable, predictable, and resilient heat sources to meet their needs. Ideally, these sources should not impose burdens on the heat users, such as requiring consistent heat off-take from industrial sources. This is especially critical for smaller heat users, where the cost of establishing and maintaining redundant heat generation facilities can erode the cost benefits of using third-party excess heat. For larger heat users, such as district heating utilities, the heating capacities of industrial companies are often small compared to the utility's overall demand.

Furthermore, district heating utilities typically operate multiple heat generation plants and thermal energy storage facilities, which, in principle, allow them to absorb the often-intermittent nature of industrial excess heat without disrupting their operations. However, as their traditional business model relies on supplying long-term, cost-stable heat from predictable sources such as boilers, cogeneration plants, or geothermal energy, utilities often lack insight into the

requirements of industrial production processes. They also seek to avoid exposing themselves to risks associated with excess heat recovery operations, such as costly interruptions to the underlying industrial processes.

Given these challenges and the general misalignment between the business models of industries and utilities, robust solutions are needed to mitigate the perceived risks for both stakeholders. To address this, Danfoss has developed a dedicated heat recovery station. The principle of the heat recovery station is to be non-intrusive, by connecting industrial excess heat to third parties through an indirect mechanism, such as heat exchangers, which physically separates the industrial system from the excess heat users.

The primary (excess heat) side of the heat recovery station connects to the cooling system of the industrial facility, while the secondary (heat recovery) side provides third-party access to the excess heat, without directly affecting the industrial system. Depending on the cooling and heating demands, the heat recovery station can partially or fully meet the industry's cooling requirements. If only partially fulfilled, the industry can supplement cooling using its own units.

Depending on the temperature requirements of the heat user, the secondary side can either be connected directly to the subsequent heat distribution system, for example a district heating network, or via heat pump, which boosts the temperature level of the recovered excess heat to the required level of the heat distribution system.

By creating a clear separation between the operation of the industrial cooling system and the heating system of the heat users, the risks are significantly reduced. This separation simplifies the business model for excess heat recovery operations.

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5. FUTURE-PROOF BUSINESS MODELS

Authors: Robert Müllehner (EI-JKU), Simon Moser (EI-JKU), Gabriela Jauschnik, Nico Marx (AIT)

This chapter is structured around three central research questions: (1) What could a viable business model for the external utilization of excess heat look like? (2) How do cooperations between industrial partners emerge? (3) What risks and barriers can be identified, and what methods exist to overcome them?

This subtask consists of a collection of individual papers and follows a structured approach comprising methodology, results, and interpretation.

5.1 METHODOLOGY

The methodological approach of this subtask is grounded in a comprehensive literature review of relevant scientific papers concerning the external utilization of excess heat. A systematic search and selection process was conducted to identify relevant sources addressing business models, cross-organizational cooperation, associated risks, and potential implementation barriers.

Most of the elaborated results have been published in a peer-reviewed article (Moser and Jauschnik, 2023). Accordingly, the content presented in this subtask is largely based on and reusing material from that publication, with a consistent, academically validated foundation.

The selected literature was analysed to extract recurring themes, general insights, and conceptual frameworks. These elements were then processed and integrated to develop an overview that serves as the basis for further interpretation and discussion within the sub-task.

5.2 RESULTS: FUTURE-PROOF BUSINESS MODELS

In the following chapter, the findings derived from the literature review are presented in a structured manner, addressing the research questions outlined in the introduction.

5.2.1 EVALUATION OF BUSINESS MODELS OF EXTERNAL EXCESS HEAT

In simplified terms, cash flows arise in two main phases: during the investment phase of project implementation, where expenditures are primarily incurred by both cooperation partners, and during the operational phase, in which the heat off-taker (typically a district heating network operator) makes payments to the supplying industrial partner (Moser and Jauschnik, 2023).

This is also illustrated in Figure 30, which is based on the cost comparison presented by Moser et al. (2020) and further developed in the paper by Moser and Jauschnik (2023). The resulting cost components and cash flows are summarized in this figure.

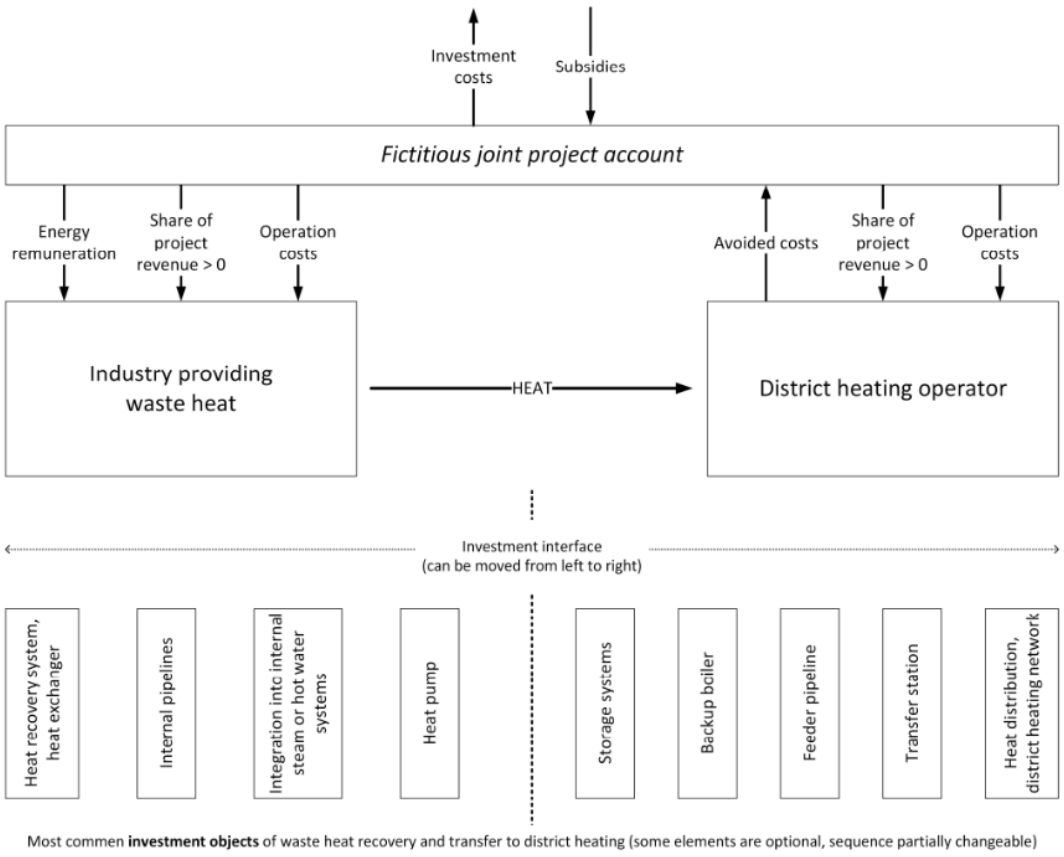


Figure 30: Payment flows of an excess heat to district heating business model. Source: (Moser and Jauschnik, 2023)

INVESTMENT

According to Moser and Jauschnik (2023), two main approaches are used to distribute investment costs:

- Shared investment, e.g., at the interface (heat meter, transfer station), where both parties contribute.
- Single-party investment, where the district heating operator bears full responsibility.

Findings indicate that industrial actors are generally more willing to provide excess heat if no additional costs or investments are required on their part. This is supported by Fritz et al. (2022), who found that cost-free integration is a key enabler of cooperation.

Moser et al. (2020) emphasize that such projects must first be economically viable for all parties involved. They introduce a hypothetical joint project account, into which all revenues (e.g., payments, avoided costs) are credited and from which all expenditures are deducted. These include:

- Initial investment,
- Operating and maintenance costs,
- Opportunity costs (e.g., lost revenues from electricity generation).

A net economic surplus must result and be distributed fairly among partners.

BILLING STRUCTURES

Energy deliveries are typically billed per kilowatt-hour (kWh), with prices indexed to benchmarks such as the consumer price index or energy commodity prices (electricity, gas, heating oil). In some cases, a reduced tariff applies during investment payback, followed by indexed pricing and profit-sharing mechanisms.

Heat pricing often reflects investment and operational responsibility:

- Higher compensation is given to partners delivering high-temperature heat, handling peak loads, or investing in transport infrastructure.
- Lower compensation is given for low-temperature or low-energy heat supplies, with price differences up to a 10:1 ratio (€/MWh) reported.

Delivery obligations vary across projects. While many have no binding supply requirements, others include conditional obligations or guaranteed minimum delivery, depending on network demand. Fixed fees or availability payments were generally not observed. In some cases, additional fees are charged for site use, interface infrastructure, or maintenance services (Moser and Jauschnik, 2023).

PAYBACK PERIOD

The expected payback period is a key factor in investment decisions. Moser and Jauschnik (2023) found an average payback period of 9 years, which is substantially longer than the typical industrial benchmark of 3 years (Moser et al., 2020).

Moser and Jauschnik (2023) conducted qualitative interviews (N=8) that provide further insight. These interviews revealed that experienced project developers often accept **6–7 years payback**. In a different survey, Fritz et al. (2022) found that more than two-thirds of the surveyed stakeholders expected a payback period of less than seven years.

Non-monetary factors such as corporate image, sustainability strategies, and regional engagement can increase tolerance for longer payback periods—linked to motivations such as strengthening local ties (Fritz et al., 2022).

5.2.2 ADVANTAGES AND DISADVANTAGES OF INTERNAL AND EXTERNAL EXCESS HEAT UTILIZATION

To understand why it may be relevant to consider the external use of industrial excess heat, the following chapter outlines the advantages and disadvantages of internal use, external use, and non-utilization of excess heat.

As part of the INXS project, a survey on cross-company excess heat utilization was conducted. Four organizations participated, providing responses from a total of 16 individuals, with some data already pre-aggregated by the respective organizations. Participants received an Excel-based response form accompanied by the following task:

“Take the perspective of a manufacturing company with technical excess heat potential. Internal use, external use, or no use of the excess heat is possible. Please specify the advantages and disadvantages of each option.” (Hammer et al., 2023)

The collected responses were subsequently consolidated to provide an overview of the advantages and disadvantages associated with internal, external, and non-utilization of excess heat.

NO UTILIZATION OF EXCESS HEAT

The survey analysis shows that, from an economic perspective, different assessments of the status quo were formulated. Potential advantages cited included the elimination of investment costs, the avoidance of replanning in the production process, and the absence of training measures or structural modifications. Organizational aspects such as independence from external stakeholders and the reduced need for coordination were also rated positively. At the same time, however, various challenges were identified, including high energy costs, CO_2

emissions, a perceived inefficient use of energy, and a potentially increased cooling requirement due to unused excess heat. Furthermore, a lack of knowledge about alternative courses of action was repeatedly cited as a barrier from a strategic and communicative perspective. (Hammer et al., 2023)

INTERNAL UTILIZATION OF EXCESS HEAT

The survey results on the internal utilization of excess heat highlight a multitude of potential advantages and disadvantages from an economic perspective. Potential advantages cited included a reduction in final energy consumption, increased energy efficiency, and savings in fossil fuels and CO_2 emissions. Furthermore, positive effects on independence from external actors and volatile energy markets, as well as a potentially favourable external perception (image gain), were highlighted. From an organizational perspective, the availability of internal process data and the ease of calculating the effects of the measures were particularly considered advantageous.

At the same time, various challenges were addressed. These include the necessary investment costs, increased effort for operation and maintenance, and possible downtime during construction work. Technical limitations, such as limited usability due to low excess heat quality or the necessary additional space requirements, were also identified. Possible internal dependencies between processes and any approval required due to plant changes were also mentioned as relevant aspects. (Hammer et al., 2023)

These advantages are also discussed by Hirzel et al. (2013), who conducted a literature review analysing the pros and cons of industrial excess heat utilization.

EXTERNAL UTILIZATION OF EXCESS HEAT

In their 2020 study, Moser and Lassacher (2020) identified Austrian companies that have implemented excess heat utilization systems. They concluded that, in most cases, the recovered excess heat is fed into district heating networks, highlighting a widespread form of external use in practice.

The INXS project investigated the external use of industrial excess heat through a comprehensive survey. The results highlight a broad spectrum of perceived opportunities and challenges (Hammer et al., 2023).

From an economic perspective, respondents highlighted revenue opportunities from selling excess heat, reductions in energy costs, and cost efficiencies through external collaboration. Additional advantages included shared infrastructure, grid feed-in options, and the strategic use of otherwise unutilized heat, alongside image-related benefits such as improved visibility, climate protection, and strengthened cross-company cooperation. Conversely, barriers were seen in high investment costs, organizational and contractual complexity, uncertainties

regarding heat availability, risks of external dependency, technical requirements, difficulties in assessing economic value, and limitations posed by geographical distance.

In summary, the findings reflect a clear tension between economic opportunities and operational or organizational risks in the external use of industrial excess heat. (Hammer et al., 2023)

5.2.3 EXAMPLES OF IMPLEMENTED BUSINESS MODELS FOR EXCESS HEAT UTILIZATION

This section provides exemplary descriptions of implemented business models that utilize excess heat. A more comprehensive compilation and detailed analysis of various excess heat utilization business models is presented in section 2 where different approaches, frameworks, and case studies are systematically documented and discussed.

INTERREGIONAL HEAT TRANSMISSION NETWORKS TO ENABLE INDUSTRIAL EXCESS HEAT

The following results originate from the Heat Highway project, which investigated the feasibility and benefits of supra-regional district heating networks for efficient excess heat utilization, as conceptually elaborated in Moser and Puschnigg (2021).

Supra-regional district heating networks (SR-DHN) serve as practical examples of how interregional heat transmission can enhance the utilization of industrial excess heat. By connecting district heating systems across regions, such networks enable a more flexible use of sustainable heat sources.

The economic feasibility of a supra-regional district heating network connecting the Austrian cities of Linz and Wels, located about 30 km apart, was investigated. A clear seasonal pattern emerged: in winter, when heat demand is high, most local heat generation units are already fully utilized to meet their own city's demand, leaving little surplus to be shared between cities. In summer, demand is low, and typically one waste-to-energy CHP unit is sufficient to meet the needs. The greatest potential for cross-city heat exchange occurs in the transition periods of spring and autumn, during which excess heat from Wels can be used to reduce gas-based heat generation in Linz. (Moser and Puschnigg, 2021). The economic modelling tool used in the project is based on the Heat Merit Order. Importantly, the analysis considered only variable costs (e.g., fuel, CO_2 certificates, operational costs) and not fixed costs such as investments, personnel, or maintenance during downtime. Also, technical limitations like ramp-up behaviour or heat transport losses were not accounted for.

The economic feasibility of connecting the district heating networks of Linz and Wels through a supra-regional district heating network (SR-DHN) was analysed. Results indicate that the SR-DHN achieves an average annual reduction of 16.3% in marginal costs and approximately

15% lower CO_2 emissions compared to the standalone Linz network. Cost benefits arise mainly from the availability of low-cost generation capacity in Wels combined with its lower heat demand, enabling more efficient heat dispatch. Connecting individual district heating networks thus proves economically and environmentally advantageous. However, practical validation is necessary to confirm that cost savings, accounting for capital expenditures and payback periods, ensure overall economic viability. Future integration of renewable heat sources, industrial excess heat, or thermal energy storage could further increase savings (Rusch and Moser, 2025).

5.2.4 ECONOMIC EVALUATION METHODOLOGY FOR DETERMINING THE EXCESS HEAT VALUE

Building on the general investment and billing principles described above, the HY2HEAT project (Puschnigg et al. 2025) developed a practical method to calculate the economic value of excess heat from electrolysers, and its use in district heating systems. The approach was tested in Bodø, Norway, and described in detail by Tommasini et al. (2025). It is based on comparing two system states to find how much a district heating operator could pay for the heat without increasing total costs.

In HY2HEAT, two cases were modelled, using the techno-economic optimizing framework IESopt, for one year. First, the reference case, where district heating is supplied by existing generation units. Second, the integration case: excess heat from the electrolyser is recovered through a heat exchanger and upgraded with a heat pump if deemed feasible by the optimizer.

All investment, operating, and electricity costs are included. The difference in total annual costs between the two cases gives the value of the recovered heat.

$$WH\ Value = \frac{C_{ref} - C_{WH}}{Q_{WH}} \qquad (5.1)$$

C_{ref} are the total annual costs without excess heat use, C_{WH} with excess heat use, Q_{WH} the annual amount of heat used in MWh. The result gives the maximum price per MWh that the district heating operator could pay while keeping overall costs unchanged.

The result defines a range for possible pricing. If the heat is provided for free, the district heating operator gains the full benefit while the electrolyser only saves cooling costs. If the full theoretical value is paid, the electrolyser gains the maximum benefit and the operator none. Real projects are usually between these points. The negotiated price decides how the benefit is shared.

In HY2HEAT, the method was applied to three locations: Bodø in Norway, Tallinn in Estonia, and Jenbach in Austria. The calculated excess heat values were between 20 and 30 €/MWh depending on temperature level, network temperature, and local energy prices.

In Bodø, using excess heat at 55–75°C from a 20 MW alkaline electrolyser reduced the district heating cost (LCOH) by up to 24% and the hydrogen cost (LCOH2) by about 7% (Tommasini et al. 2025). These numbers show that both partners can profit if the technical and commercial setup is right.

The same logic can be used for other excess heat sources such as data centres, biogas plants, or industrial processes.

1. Define reference and integration cases.
2. Calculate total system costs for both.
3. Divide the cost difference by the recovered heat.
4. Use the result as the upper limit of a fair price.

The method gives a simple way to quantify the value of excess heat and to define a price range for contracts between the heat supplier and the district heating operator.

5.2.5 COOPERATION BETWEEN INDUSTRIAL PARTNERS

This chapter addresses conditions that foster cooperation between industrial partners.

The question of how collaborations between industrial and district heating partners emerge was examined by Moser and Jauschnik (2023). The authors first investigated who typically initiates the idea of utilizing excess heat through inter-organizational cooperation. As summarized in

Table 12, responses from companies already engaged in such collaborations indicate that a wide range of actors—both internal and external—may act as initiators.

Table 12 Take-out of the stakeholder-related responses to the question of who initiated the cooperation. Source: (Moser and Jauschnik, 2023)

Question (Multiple Choice)	n	Amount
Idea of our (at that time) management	n = 18	5
Idea of our employees	n = 18	9
Idea of the management of the cooperation partner	n = 18	7
Idea of the employees of the cooperation partner	n = 18	1
Third party: Mayor, site agency, advocacy group or other	n = 18	5
Third party: Audit, consultant, research	n = 18	3

In 14 out of 30 reported cases, the industrial company's own management or employees were the primary initiators of cooperation, with employees playing a more prominent role. In contrast, the cooperation partner was the initiator in only eight cases. External stakeholders—particularly local policymakers such as mayors and municipal agencies—were also recognized for their constructive influence, while supra-regional actors were mentioned only in the context of funding and subsidies.

These findings are corroborated by the results of Fritz et al. (2022), which also emphasize the critical role of individual actors within companies in driving excess heat integration into district heating systems. **The presence of motivated individuals with a strategic or technical vision appears to be a recurring success factor.**

The next question addresses the motivation and nature of cooperation. To better understand the background of collaboration development, three types of motivation were identified (Moser and Jauschnik, 2023):

1. Known people / good contact: Collaborations initiated through existing trust-based relationships and regular communication.
2. Current interest: Partnerships driven by specific, often situational triggers such as new buildings, site expansions, or strategic developments.
3. Long sought, finally realized: Collaborations that had been considered for an extended period but were only implemented when new actors or altered circumstances made the project economically or technically feasible.

Roughly one-third of the collaborations were based on a constructive and trust-based dialogue environment, involving transparent data exchange and fair negotiations. The remaining two-thirds were primarily driven by technical or economic motives, such as new investments or

operational upgrades—either initiated spontaneously or emerging from long-term considerations (Moser and Jauschnik, 2023).

To investigate whether structural or operational changes on the part of either partner facilitate cooperation, another survey question focused on the timing of collaboration. The hypothesis tested was whether a major change at one of the partners (e.g., commissioning of a facility or construction project) served as a trigger for cooperation, see Table 13.

Table 13: Responses to the multiple-choice question on whether the timing of the establishment of the collaboration is related to changes at the decreasing and/or providing partner company. (Moser and Jauschnik, 2023)

Categories	n	Amount
"The cooperation started at the time of the start of operation/a major change at the accepting partner company (e.g., with commissioning of district heating network)"	n = 18	4
"The cooperation started at the time of the start of operations/a major change at the providing partner company (e.g., with new construction of facilities)"	n = 18	4
Both	n = 18	4
None	n = 18	6

In six cases, no direct trigger related to structural change was selected, suggesting that other soft factors—such as relationship networks—played a more decisive role. The authors interpret this as follows: while technical developments often catalyse cooperation, strong personal networks or previous shared experiences (e.g., university ties or regional events) can enable partnerships even in the absence of major organizational shifts (Moser and Jauschnik, 2023).

5.2.6 POTENTIAL BARRIERS TO (INTER-COMPANY) EXCESS HEAT UTILIZATION AND SOLUTIONS

Rodin and Moser (2021) propose a categorization of barriers to industrial excess heat utilization, based on a literature review. The individual barriers within these categories are further detailed in the work of de Bruyn et al. (2018). This clustering was also adopted in the context of the INXS project, serving as a framework for identifying and analysing potential obstacles. (Hammer et al., 2023)

The categorization of potential barriers is as follows:

- Economic barriers
- Social/Managerial barriers
- Framework barriers
- Technical/Engineering barriers
- Information provision barriers

POSSIBLE SOLUTIONS TO OVERCOME THE HURDLES

In principle, a distinction can be made between technical, organizational, legal, and financial hurdles. Possible solutions to overcome these hurdles are described below.

5.2.7 ENHANCEMENT OF ORGANIZATIONAL FRAMEWORK

Organizational framework conditions primarily involve awareness of existing excess heat potentials and the alignment with corresponding demand. This applies not only to industrial actors but also to network operators, local communities, and different departments within a company. Consequently, internal knowledge regarding a company's own excess heat sources as well as the available technical utilization options, such as cascaded heat use, is required (Hammer et al., 2023).

Moser and Jauschnik (2023) identified several factors that can initiate cooperation. One important driver is the existence of close relationships between potential partners, characterized by mutual understanding, regular exchange, and trust. Even in the absence of such ties, cooperation may arise when significant changes occur at the receiving company, such as the commissioning of a district heating network.

Their findings further show that well-established contact provides a direct and reliable basis for communication, while external intermediaries can also play a role in facilitating initial connections. In all cases, the first contact is considered a decisive step toward implementation.

After initial contact, key issues need to be clarified, including the operation of the required infrastructure, the assurance of supply security, and the pricing of heat transfer. (Hammer et al., 2023)

5.2.8 PARTIAL AND TECHNICAL CHARACTERIZATION OF EXCESS HEAT POTENTIALS

The excess heat potentials identified in the INXS project have been integrated as technical potentials into the Austrian Heat Map. Three map layers display both Bottom-Up and Top-

Down assessed potentials from industrial facilities, as well as potentials from wastewater treatment plants. Bottom-Up industrial potentials and those from treatment plants are mapped at precise locations, whereas Top-Down potentials are aggregated at the postal code level. Most Bottom-Up potentials were also classified by temperature range and assigned to multiple excess heat sources.

This spatial representation makes the INXS project data accessible and tailored to different stakeholders. By linking the data with existing district heating networks in the Austrian Heat Map, detailed spatial analyses can be conducted. This organizational measure enables the freely accessible Heat Map to serve as an excess heat platform, allowing planners, network operators, municipalities, industrial and commercial facilities, and public authorities to make preliminary assessments and pre-planning for potential excess heat utilization projects (Hammer et al., 2023).

5.2.9 POSSIBLE LEGAL AND POLICY ACTIONS

The primary area of action is the recognition of excess heat in the context of the section "Classifying excess heat as a renewable energy source." In the field of excess heat utilization, this mainly concerns the Energy Efficiency Act (EEffG), which aims to improve energy efficiency while ensuring supply security, increasing the share of renewable energy in the energy mix, and reducing greenhouse gas emissions. Additionally, it seeks to provide positive economic impulses.

The consortium of the INXS-project argues for policy intervention in terms of an obligation to report annual energy consumption, which would then be made visible in a database for research institutions and authorities (with privacy protections), like the greenhouse gas emissions reported by companies and facilities participating in the EU Emissions Trading System (ETS). In a further stage, this system could also include mandatory data on emissions, wastewater, exhaust air, product flows, etc., specifying temperatures and mass flows, to enable reliable energy spatial planning for authorities, research institutions, planners, etc. It could also be considered to have these data verified by external auditors every few years, who would also provide advisory support (like ETS or EMAS). Such measures are politically challenging to implement, but their potential benefits should be acknowledged. (Hammer et al., 2023)

The INXS project (Hammer et al., 2023) references the financial framework conditions in Austria as outlined in Annex 15 of the Industrial Technology Collaboration Programs (TCPs) by the International Energy Agency (IEA):

INVESTMENT SUBSIDIES

The Environmental Funding Domestic (UFI) program, managed by Kommunalkredit Public Consulting (KPC), provides financial support for energy efficiency investments, including excess heat recovery, heat pumps, efficient production processes, heating system optimization, and heat distribution networks.

ENERGY AUDITS

The “SME Energy Checks” program supports small and medium-sized enterprises (SMEs) by funding initial energy audits, implementation of measures, and energy management consulting to reduce greenhouse gas emissions.

BANK-BASED FINANCING

Austrian banks offer favourable loans for energy efficiency and renewable energy projects. Additionally, Austria Wirtschaftsservice GmbH (AWS) provides ERP loans, loan guarantees, and non-repayable grants.

CONTRACTING MODELS

Contracting shifts investment and performance risks to service providers. Energy supply contracting is used for heat and power, while energy performance contracting (EPC) focuses on optimizing building systems and industrial processes.

TRUSTEE FINANCING PLATFORM

Developed under an EU project, TrustEE offers a structured refinancing mechanism for energy efficiency and renewable energy projects by evaluating projects technically and economically and providing standardized reports for refinancing.

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ABBREVIATIONS

Abbreviation	Meaning
AEE	District Heating Systems
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
DHC	District Heating and Cooling
EEX	European Energy Exchange
EEffG	Energy Efficiency Act
EED	Energy Efficiency Directive
EUDCEAR	EU Data Centre Energy Audit and Reporting
EUDP	Energy Technology Development and Demonstration Programme
EU-ETS	European Union Emissions Trading Scheme
GHG	Greenhouse Gas
GIS	Geographical Information System
IES	Integrated Energy Systems
InES	Industrial Energy Systems
LCOE	Levelized Costs of Energy
RED III	Renewable Energy Directive
SNG	Synthetic Natural Gas
SR-DHN	Supra-regional District Heating Network
TSN	Thermal Source Network
WWTPs	Wastewater Treatment Plants

APPENDIX

SUPPLEMENTARY MATERIAL ON CHAPTER 4.4.1

RELEVANT TECHNICAL PARAMETERS FOR EXTERNAL EXCESS HEAT INTEGRATION

An important factor is the **temperature** of the excess heat source, primarily in terms of cost-effectiveness of utilizing the heat. If the excess heat is at a low temperature, a heat pump may be necessary to raise the temperature to meet the requirements of the DH system. Depending on the temperature levels of the DH system, the capital and operational expenditures of the heat pump, as well as those of any accompanying heat exchangers, the economic added value of utilizing external excess heat sources may be compromised.

The **maximum thermal capacity** P_{max} of the excess heat source defines the maximum amount of heat that can be supplied by the external source per unit of time.

The **annual heat potential** measures the amount of heat that an excess heat source can provide within a year. It can be used to assess the quality and usability (e.g., supply security) of an excess heat source with regard to integration into an existing network.

The **pressure** within the excess heat source supply line needs to be considered during integration, as increases in pressure in a pipe increase the volumetric flow rate of the contained heat carrier. Due to this relationship, the performance of heat exchangers in the system may be adversely affected by increases in pressure, due to less time being available for heat exchange to take place. In addition, district heating networks aim for stable pressure in the system to ensure consistent flow rates. As such, pressure fluctuations caused by an external heat source reduce the overall efficiency of the network.

The **volumetric flow** rate in a system (often given in m^3/s or L/min) is determined by pressure drop and allowable flow velocities. This needs to be considered when integrating an existing external excess heat source into an existing district heating network; for untapped or planned excess heat sources, the layout and design must be compliant with the network they will feed into. Typically, the maximum permissible pressure drop is around 150 Pa/m. The maximum flow velocity is dependent on pipe dimensions; larger pipe diameters allow for higher maximum flow velocities. For large dimensions, velocities of 3-5 m/s are realistic. Velocities beyond this increase the risk of erosion and are thus uncommon.

The **distance** between the excess heat source and the DH grid is also an integral part of external excess heat utilization. The greater the excess heat capacity, the greater the transportation distance that can be economically justified. This is due to larger capacities making relative heat loss from transportation negligible, thus reducing the temperature drop over the transportation distance. At the same time, larger distances require longer supply pipes, leading to increased capital investments. These may increase further based on soil characteristics, which can affect the intensity of required excavation work, and the presence of existing surface coverings, like sealed surfaces.

HEAT TRANSFER STATION PARAMETERS

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A heat transfer station serves to transfer heat in accordance with its intended use in terms of pressure, temperature, and volume flow; from a heat consumer in the district heating network to the heat consumer, or from a heat source to the district heating network [DIN4747]. The main function of the heat transfer station is therefore to transfer thermal energy at a defined temperature level. Furthermore, the heat transfer station also performs an energy balance of the transferred heat; this energy balance can be used for an economic and ecological evaluation of the transferred heat. In most cases, heat transfer stations are implemented by means of hydraulic separation between the district heating network and the connected system [Nuss17]. A heat transfer station for the integration of decentralized heat sources can, in principle, be connected in series and in parallel to the heat generators, so that three variants of the connection can be distinguished [Buca06]:

- Return flow to flow: The return flow of the district heating network is heated to the flow temperature by the decentralized heat source and fed directly into the flow of the district heating network.
- Return flow increase: The return flow of the district heating network is heated by the decentralized heat source and fed to the heat generators.
- Flow temperature increase: The flow of the district heating network is reheated by the decentralized heat source so that the flow temperature after the heat generators is increased

In most cases, connecting the return flow to the flow is preferable, as this allows the heat from the heat source to be used more efficiently than when connecting the flow to the return flow, and does not impair the energy efficiency of the downstream heat generators [Buca06; Halm14]. Regarding the temperature level of the heat source, e.g., industrial excess heat, three connection options must also be considered when connecting the return flow to the supply flow [Star20]:

- Direct integration: The temperature of the heat source is above the flow temperature of the district heating network, so that the heat can be integrated directly via heat exchangers.

- Partial direct integration: The temperature of the heat source is between the flow and return temperatures of the district heating network, so that the temperature of the heat source must be reheated electrically or by combustion processes.

- Indirect integration via heat pump: The temperature of the heat source is below the return temperature of the district heating network, so the temperature of the heat source must be raised via a heat pump.

In addition to the possibility of feeding industrial excess heat into district heating networks, industrial companies can also obtain heat from district heating networks to provide space heating, hot water, or process heat. Depending on the characteristics of heat requirements and system components in industrial energy systems and district heating networks, it makes sense to feed heat in one direction or the other. If it makes sense to purchase heat at certain times and sell (surplus) heat at other times, an industrial company can also be connected to a district heating network in a bidirectional manner as a so-called prosumer [Bran14]. For this purpose, a bidirectional heat transfer station must be implemented, which enables the purchase and sale of heat through appropriate interconnection. Possible bidirectional heat transfer stations with corresponding operating strategies are described in [Anco15; Rose17; Pipi21; Kohn21a].

Definitions for district heating connection and heat transfer station: The district heating connection comprises all system components in which investments are made while connecting an industrial energy system to a district heating network. A fundamental part of the district heating connection is the heat transfer station, which is responsible for transferring heat at a defined temperature level and for the energetic, economic, and ecological balancing of the transferred heat [Star20]. The heat transfer station can consist of various system components and can be designed to be bidirectional [Kohn21a].

HEATING AND COOLING TECHNOLOGY

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In the following, different types of technical systems for heat and cold generation and thermal energy storage are characterized. System components of the industrial heating and cooling supply are presented in relation to the generated heat output or cooling output, providing thermal efficiency and input power. For a detailed explanation of the functionality of individual industrial heating and cooling supply systems, please refer to [Hess12; Bles17; Dehl20].

A distinction can be made between fuel-based and electricity-based heat generators for the provision of heat. The former converts chemical energy from fuels (fossil or renewable) into heat through combustion processes. Steam is generated from the resulting exhaust gas (steam boiler), or heated water (low-temperature boiler, condensing boiler) is provided [Bles17]. In electricity-based heat generators, a distinction is made between different types of resistance heating technologies, such as electric and electrode boilers on the one hand and heat pumps on the other [Bles17]. Heat pumps can use a cooling capacity as thermal power from a low temperature level, e.g., from the ambient air, the ground, well water or cold-water networks and provide heat at a higher temperature level as a thermal capacity by using electrical power. For this process, the coefficient of performance (COP) is used as a parameter for efficiency, which represents the ratio between heat output and electrical input and is substantially higher than the efficiency of conventional heat generators because heat pumps transfer heat instead of generating it directly, making better use of the available energy. However, due to the high dependence of the COP on the required temperature lift and the temperature of the heat source, its use must be evaluated on a case-by-case basis. The upper limit of the heat pump COP is given by the Carnot efficiency [Zaho13].

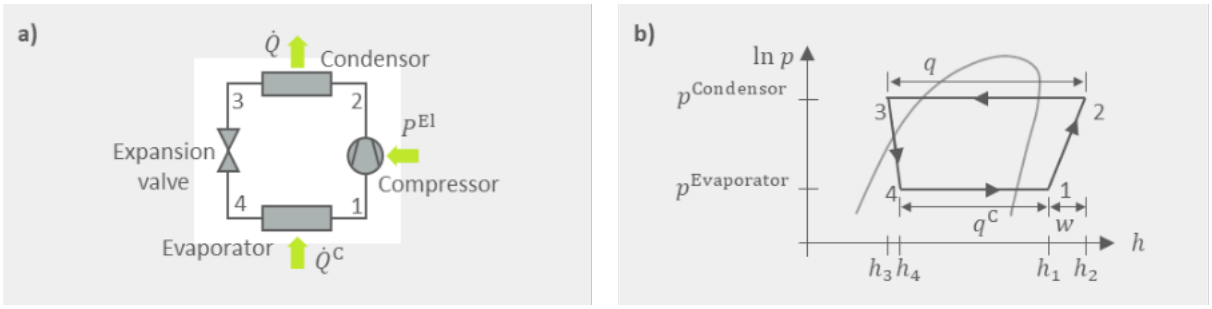


Figure 31: Schematic and process of a heat pump. a: Schematic with components, b: thermodynamic process. PEl: Electrical power, ˙Q: Condenser heat output, ˙QK: Evaporator heat output or cooling capacity, p: pressure, h: specific enthalpy, q: specific heat, w: specific work as electrical energy. (Kohne 2023)

In addition to pure heat generators, CHP systems are also used in industrial heating networks [Flum21]. These fuel-based systems generate both electrical energy, using motors or turbines, and thermal energy from exhaust gas and engine heat, e.g., gas turbines are often used to provide steam and CHP plants are usually used to provide warm or hot water [Dehl20]. To achieve high utilization hours and overall efficiencies in the form of fuel utilization, they were often planned as the base load for heat supply [Zaho13]. Due to changing regulations, CHP systems are currently planned instead for residual heating and electricity loads. The fuel utilization factor is the sum of the thermal and the electric efficiency. It is calculated by the sum of the heat output used and the electrical output generated in relation to the energetic output of the fuel from the mass flow and the calorific value.

In industrial cooling supply, a distinction can be made between active and passive systems for cooling. *Active systems* include electrical, thermal, and mechanical chillers. Mechanical chillers are referred to as electricity-based compression chillers, which work on the same principle as heat pumps. However, chillers are used to provide cooling, which is why the Energy Efficiency Ratio (EER) refers to thermal cooling power. As with heat pumps, the EER is dependent on the temperature levels [Hess12]. Unlike chillers, *passive cooling generators* work by means of convective heat dissipation or evaporative cooling. A distinction is made between dry cooling towers (convection), wet cooling towers (evaporative) and hybrid cooling towers (combination). The coefficients of performance of passive cooling generators can be significantly higher than those of active cooling generators due to direct heat dissipation, however, they are heavily dependent on the ambient temperature and humidity, meaning that their utilization is dependent on the ambient conditions [Reis22]. In industrial cooling, active and passive cooling generators are often combined and interconnected for different temperature levels [Webe14].

Thermal energy storage (heat and cold storage) is also used in industrial heating and cooling supply systems to balance the heating and cooling capacity between energy converters and energy requirements, as well as to minimize investment costs into generating systems. As the energy demand in thermal systems depends on various factors such as the outside temperature or production schedules, the use of these so-called buffer storage units or passive storage units allows heat and cold generators to be used more energy-efficiently (in better operating points) [Dehl20]. In addition to making better use of existing energy converters, thermal energy storage systems can also be controlled by other factors such as energy purchase prices (cost perspective) or availability of renewable heat sources (environmental perspective) and can therefore be used actively for operational system optimization (e.g., peak load shaving) [Flum21].

Both sensible or latent heat storage systems are commonly used in industrial heating and cooling supply systems. In sensible heat storage systems, heat is stored by changing the temperature of storage medium (usually water). A special form is layered storage, which enables exergy-optimized storage of thermal energy (temperature layers) via individual layers. Latent heat accumulators store energy via the phase change, as phase changes enthalpy with more constant temperatures [Dehl20].

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