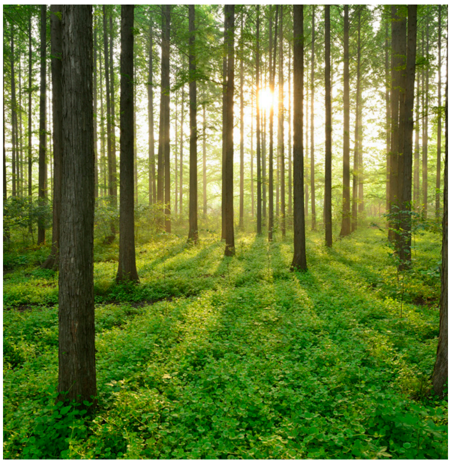
70 NEW POSSIBILITIES FOR DISTRICT HEATING

REPORT 2024:1040



FUTUREHEAT

Energiforsk

70 New Possibilities for District Heating

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Foreword

Swedish district heating was an early adopter of replacing fossil fuels with other raw material bases, but with retained technology. International district heating has now also begun to phase out fossil fuels as a result of international climate policy, and since the rest of the world does not have the same possible raw material base as Sweden, rapid development has started towards new district heating technology. The aim of this project is to compile the latest state of the art in the district heating and cooling sector. The report can be used as a support in the form of an idea bank for both technical and strategic choices.

The project has been led and carried out by Henrik Gadd from Halmstad University together with Mohammad Saeid Atabaki, Mei Gong, Erik Möllerström, Heidi Norrström, Fredric Ottermo, Urban Persson, Luis Sanchez Garcia and Sven Werner.

A reference group consisting of Dado Hadziomerovic, Vattenfall (sammankallande); Einar Port, Mälarenergi; Anders Einarsen, Mälarenergi; Johan Andersson, Mälarenergi; Anders Gunnarsson, Borås Energi och Miljö; Niklas Olsson, Tekniska verken i Linköping; Jessica Englund, E.ON Energiinfrastruktur; Magnus Revland, Finspångs tekniska verk; Cecilia Bergquist, Halmstad Energi och Miljö och Martin Marklund, Södertörns fjärrvärme have followed and quality assured the project.

The project is part of the Futureheat programme, whose long-term goal is to contribute to the vision of a sustainable heating system with successful companies that exploit new technological opportunities and make the most of the societal investments made in district heating and cooling. This project is part of the third phase of the programme.

The program is led by a steering group consisting of Cecilia Bergquist, Halmstad Energi och Miljö (chairman); Erik Axelsson, Göteborg Energi; Stefan Hjärtstam, Borås Energi och Miljö; Peter Mattsson, Södertörns Fjärrvärme; Svante Carlsson, Skellefteå Kraft; Stina Berg, Tekniska Verken i Linköping; Dado Hadziomerovic, Vattenfall; Fabian Levihn, Stockholm Exergi; Lisa Granström, Mälarenergi; Magnus Ohlsson, Öresundskraft; Magnus Revland, Finspångs Tekniska Verk; Harald Andersson, E.ON Energiinfrastruktur; Johan Thelander, Karlstads Energi; Ulf Lindqvist, Jämtkraft; Patrik Grönbeck, Norrenergi.

The authors are responsible for the content of the report.

Carolina Holmberg, program manager Futureheat

Summary

The ongoing transformation in European district heating systems from the usage of fossil-based technologies to non-fossil heat supplies is summarised by a collection of 70 possibilities linked to decarbonisation. These possibilities are exemplified by 284 implemented, planned, or proposed cases. The 70 possibilities for decarbonised district heating include using heat, connecting customers, moving heat, storing heat, removing carbon dioxide, and supplying heat together with some features for the entire value chain, to heat usage from heat generation or recycling. This collection of 70 possibilities is neither complete nor does it contain any recommendations for the possibilities or advocate for specific possibilities.

The purpose of this project was to provide an extensive inventory of decarbonisation activities recently performed by district heating operators and other heat suppliers. These decarbonisation activities include the direct substitution of heat obtained from the combustion of fossil fuels and indirect actions for obtaining more efficient district heating systems. These indirect actions reduce costs and increase revenue, thereby improving the competitiveness of district heating. The time horizon, which is linked to the EU's target for the reduction of greenhouse gas emissions by 55% compared to 1990 levels, is 2030. This inventory of early decarbonisation projects concerning district heating systems has revealed the following three key conclusions.

First, **decarbonisation activities** can be divided into substituting and supporting possibilities. **Substituting possibilities** in heat supply include linear supply from renewables, heat recycling from processes that generate excess heat, and non-fossil ways of meeting peak heat demands during very cold days. The linear heat supply is based on geothermal heat, solar heat, and electricity supply. Heat recycling is possible from various processes related to biorefineries, hydrogen supply, petrochemical plants, electricity distribution, district cooling, data centres, battery factories, food supply chains, and sewage waters. Heat storage can make heat delivery more independent of heat supply and provide additional opportunities to reduce peak loads. **Supporting possibilities** mainly comprise activities for obtaining lower temperatures in heat distribution networks to increase profitability when using low-temperature heat sources. These activities are performed when connecting customers, moving heat, and using heat. Another supporting activity is the removal of biogenic carbon dioxide from the natural carbon cycle, although an appropriate international accounting system for its removal is still missing.

Second, the **decarbonisation possibilities** of district heating systems differ from those of traditional systems based on fossil fuels. The availability of decarbonisation possibilities for district heating depends on local conditions, whereas fossil fuels are transported from available global resources and are used worldwide. Hereby, decarbonised district heating systems will not be as uniform as traditional systems based on fossil fuels. The local conditions lower the degrees

of freedom for the implementation of substituting possibilities in existing buildings and systems. Hence, it is important to adopt new methods for utilising the highest degree of freedom possible in new buildings and systems.

Third, the **common denominators** for the 70 identified possibilities are degrees of freedom for decarbonisation, action plans for achieving lower heat distribution temperatures, the use of heat pumps for upgrading low-temperature supplies to meet high-temperature demands, smart digitalisation options, clear supply responsibilities, favourable institutional frameworks, and digital planning models. These seven common denominators are efficient tools for obtaining decarbonised and more efficient district heating systems in the future. These redesigned and new systems will be somewhat different than traditional systems, which have been based on a district heating technology that was originally elaborated for systems based on fossil fuels.

Highlight cases in this report

1. **Using heat:** 8 million kg of tomatoes per year from excess heat in Frövi, case 2.4.3.
2. **Using heat:** Steam from excess heat in Mölndal, case 2.5.1.
3. **Connecting customers:** Flat substations in Frankfurt, case 3.1.1.
4. **Moving heat:** Some different supply temperatures in Chevilly-Larue, case 4.3.1.
5. **Storing heat:** Rock caverns of one million m^3 in Vantaa, case 5.6.8.
6. **Removing carbon dioxide:** Waste incineration in Oslo, case 6.2.4.
7. **Linear renewable supply:** 400 MW geothermal for Munich, case 7.2.2.
8. **Linear renewable supply:** 64 MW Eavor loop in Geretsried, case 7.2.12.
9. **Linear renewable supply:** 110 MW solar heat in Silkeborg, case 7.6.7.
10. **Linear renewable supply:** 500 MW with sea water and heat pumps in Helsinki, case 7.8.4.
11. **Heat recycling:** Excess heat from 20 MW electrolyser in Hofors, case 8.2.1.
12. **Heat recycling:** Combined heating and cooling in cold network in Zurich, case 8.8.1.
13. **Heat recycling:** Excess heat without heat pump from data centre in Aalborg, case 8.10.1.
14. **Value chain:** 17 ways of using heat pumps in district heating systems, case 10.3.1.

Keywords

Decarbonisation, possibilities, cases, district heating, transformation, Europe

Sammanfattning

Den pågående omvandlingen av europeiska fjärrvärmesystem från användning av fossilbaserad teknik till icke-fossil värmeförsörjning sammanfattas med en utvald samling av 70 möjligheter kopplade till fossilfrihet. Dessa möjligheter exemplifieras med 284 genomförda, planerade eller föreslagna fall. De 70 möjligheterna för koldioxidfri fjärrvärme omfattar att använda värme, ansluta kunder, flytta värme, lagra värme, avskilja koldioxid och tillföra värme tillsammans med några aspekter för hela värdekedjan till värmeanvändning från värmeåtervinning eller värmegenerering. Uppsättningen av 70 möjligheter är varken komplett eller innehåller några rekommendationer för vilka möjligheter som bör användas.

Syftet med detta projekt har varit att tillhandahålla en omfattande inventering av aktiviteter för att erhålla fossilfri fjärrvärme som nyligen utförts av fjärrvärmeoperatörer eller andra värmeleverantörer. Dessa aktiviteter omfattar både direkt substitution av värme som tidigare erhållits från förbränning av fossila bränslen och stödjande indirekta åtgärder för att erhålla mer effektiva fjärrvärmesystem. Dessa stödjande åtgärder minskar kostnaderna eller ökar intäkterna som förbättrar fjärrvärmens konkurrenskraft. Tidshorisonten har varit 2030, kopplat till EU:s mål för minskning av växthusgasutsläppen med 55 % jämfört med 1990 års utsläpp. Denna inventering av tidiga projekt för fossilfri fjärrvärme har givit följande tre viktiga slutsatser.

För det första, aktiviteter för **fossilfri fjärrvärme** kan delas in i ersättande och stödjande möjligheter. **Ersättande möjligheter** i värmeförsörjningen inkluderar linjär försörjning från förnybar energi, värmeåtervinning från processer som genererar restvärme och icke-fossila sätt att möta spetsbehov under mycket kalla dagar. Den linjära värmeförsörjningen baseras på geotermisk värme, solvärme och eltillförsel. Nya aktiviteter för värmeåtervinning är möjliga från många olika samhällsprocesser, såsom bioraffinaderier, vätgasförsörjning, petrokemiska anläggningar, eldistribution, fjärrkyla, datacenter, batterifabriker, livsmedelsförsörjning och avloppsvatten. Värmelager kan göra värmeleveransen mer oberoende av värmetillförseln, vilket också ger ytterligare möjligheter att minska spetsbelastningar. **Stödjande möjligheter** innehåller främst aktiviteter för att erhålla lägre temperaturer i värmedistributionsnät, vilket ökar lönsamheten vid användning av lågtempererade värmekällor. Dessa aktiviteter utförs när man använder värme, ansluter kunder och flyttar värme. En planerad stödaktivitet är också avskiljning av biogen koldioxid från det naturliga kolkretsloppet, även om ett lämpligt internationellt ersättningssystem för detta fortfarande saknas.

För det andra, karaktären hos **möjligheterna till fossilfritt** skiljer sig från de traditionella erfarenheterna baserade på fossila bränslen. Tillgången på möjligheter till fossilfritt beror på lokala förhållanden, medan fossila bränslen transporterades från tillgängliga globala resurser, vilket gav full frihet att använda fossila bränslen var som helst i världen. Härigenom kommer fossilfria fjärrvärmesystem inte bli så

likartade som traditionella fjärrvärmesystem var med fossila bränslen. De lokala förutsättningarna för fossilfri fjärrvärme ger något lägre frihetsgrader för implementering av ersättande möjligheter i befintliga byggnader eller system. Därför är det viktigt för framtiden att utnyttja den högre frihetsgrad som är möjlig i nya byggnader och system genom att använda nya metoder mm.

För det tredje, de **gemensamma nämnarna** för de 70 identifierade möjligheterna är antal frihetsgrader för fossilfrihet, handlingsplaner för att erhålla lägre temperaturer i värmedistributionsnät, olika sätt att använda värmepumpar för att uppgradera låga framtemperaturer för att tillgodose högre temperaturbehov hos kunderna, möjliga smarta digitaliseringsalternativ, tydliga leveransansvar, gynnsamma institutionella ramar samt digitala planeringsverktyg. Dessa sju gemensamma nämnare är effektiva verktyg för att få mer effektiva fossilfria fjärrvärmesystem, eftersom den traditionella fjärrvärmetekniken en gång i tiden utformades för system baserade på användning av fossila bränslen.

Betydelsefulla fall i denna rapport

1. **Använda värme:** 8 miljoner kg tomater per år från restvärme i Frövi, fall 2.4.3.
2. **Använda värme:** Ånga från restvärme i Mölndal, fall 2.5.1.
3. **Ansluta kunder:** Lägenhetscentraler i Frankfurt, fall 3.1.1.
4. **Flytta värme:** Flera olika framtemperaturer i Chevilly-Larue, fall 4.3.1.
5. **Lagra värme:** Bergrum på en miljon m^3 i Vanda, fall 5.6.8.
6. **Avskilja koldioxid:** Avfallsförbränning i Oslo, fall 6.2.4.
7. **Förnybar linjär tillförsel:** 400 MW geotermi för München, fall 7.2.2.
8. **Förnybar linjär tillförsel:** 64 MW Eavor-loop i Geretsried, fall 7.2.12.
9. **Förnybar linjär tillförsel:** 110 MW solfjärrvärme i Silkeborg, fall 7.6.7.
10. **Förnybar linjär tillförsel:** 500 MW med havsvärme och värmepump i Helsingfors, fall 7.8.4.
11. **Värmeåtervinning:** Värme från elektrolysör på 20 MW i Hofors, fall 8.2.1.
12. **Värmeåtervinning:** Kombinerad värmning och kylning med kall fjärrvärme i Zürich, fall 8.8.1.
13. **Värmeåtervinning:** Värme utan värmepump från vattenkylt datacenter i Ålborg, fall 8.10.1.
14. **Värdekedjan:** 17 olika sätt att använda värmepumpar i fjärrvärmesystem, fall 10.3.1.

Sökord

Fossilfritt, möjligheter, fall, fjärrvärme, omvandling, Europa

Abbreviations, definitions, and vocabulary

Bidirectional connection	Connection of a customer building that encompasses heat delivery to and heat supply from the customer with a combination of supply-to-return and return-to-supply connections
Carbon dioxide removal	Methods for removal of carbon dioxide from flue gases coming from combustion of carbon-based materials
CDR	Carbon dioxide removal
CHC	Combined heating and cooling
CHC configuration	Network configuration that is based on combined heating and cooling
CHP	Combined heat and power
Circulation flow	Flow that bypasses a substation to maintain the supply temperature when no heat delivery appears in the substation (bypass and shortcut flows are synonyms of circulation flow)
Classic configuration	Traditional network configuration that uses one supply pipe and one return pipe by blending delivery and circulation flows in the return pipe
Coefficient of performance	Key performance indicator for heat pumps, defined as the ratio between the heat output and the electricity or heat inputs
Cold district heating	District heating based on a cold network
Cold network	Heat distribution network that generally requires additional heating in customer substations since ultra-low supply temperatures are used
Combined heat and power	Synergy that utilises the excess heat from thermal power generation processes for heating purposes
Combined heating and cooling	Synergy that utilises the excess heat from cooling processes for heating purposes
COP	Coefficient of performance
Cost reduction gradient	Key performance indicator for heat distribution networks, that reflects the reduction in heat supply cost when applying lower heat distribution temperatures, expressed as cost reduction per heat delivered and per reduction of the temperature level
CRG	Cost reduction gradient
Delivery flow	Flow that passes through customer substations
DHC	District heating and cooling
DHC+	The European research platform for DHC, hosted by EHP since 2009
DHW	Domestic hot water
EGS	Enhanced geothermal system
EHP	Euroheat & Power, the European association for DHC, located in Brussels and founded in Paris 1954
EU	European Union
Heat delivery	Heat delivered to customers from heat distribution networks
Heat distribution loss	Heat lost from the distribution network, defined as the difference between the heat supply into the network and the heat delivered to customers
Heat recycling	General term for the recovery of heat to be finally reused before being released to ambient temperature
Heat Roadmap Europe	Cluster project since 2012 for assessing the future heat market in the European Union, initiated by the Aalborg and Halmstad Universities
Heat supply	Heat supplied into heat distribution networks
High supply temperature	Supply temperature beyond approximately 100°C
High-temperature district heating	District heating based on high supply temperatures
HRE	Heat Roadmap Europe
IEA	International Energy Agency, located in Paris and founded in 1974
IEA-DHC	The DHC technology collaboration group within the IEA technology collaboration programme
IPCC	Intergovernmental Panel on Climate Change, formed in 1988
Low supply temperature	Supply temperature below approximately 70°C
Low-temperature district heating	District heating based on low supply temperatures
LTDH	Low-temperature district heating

LULUCF	Land Use, Land Use Changes and Forestry, one of the five baskets in the 2006 IPCC guidelines for greenhouse gas emissions
Medium supply temperature	Supply temperature between approximately 70°C and 100°C
Medium-temperature district heating	District heating based on medium supply temperatures
Modified classic configuration	Modification of the classic configuration by the introduction of a third pipe designed to accommodate the circulation flow
Multi-level configuration	Network configuration that provides more than one supply temperature
Network configuration	General term for the option to organise and manage a heat distribution network
OECD	Organisation for Economic Co-operation and Development, located in Paris
Prosumer	Customer that can also supply heat into the heat distribution network
Return-to-return connection	Substation connection that adds heat to or subtracts heat from a return pipe
Return-to-supply connection	Substation connection that adds heat to a flow from the return pipe and delivers it to the supply pipe
SAF	Sustainable aviation fuel
Substation	Installed unit that transfers and measures the delivered heat from the heat distribution network to a customer, or vice versa in the prosumer case
Supply-to-return connection	Traditional substation connection for heat delivery to a customer by the subtraction of heat from the heat distribution network
Supply-to-supply connection	Substation connection that adds heat to or subtracts heat from a supply pipe
Total flow	Sum of the delivery and circulation flows
Ultra-low configuration	Network configuration that uses ultra-low supply temperatures
Ultra-low supply temperature	Supply temperature below approximately 50°C
UNFCCC	United Nations Framework Convention on Climate Change, established in 1992
Warm district heating	District heating based on a warm network
Warm network	Heat distribution network without any additional heat supply in substations, except for customers with unusually high temperature demands

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1 Introduction

1.1 PURPOSE AND SCOPE OF THIS PROJECT

The purpose of this project was to provide an extensive overview of implemented, planned, and proposed decarbonisation activities early performed by district heating companies and other heat suppliers. These decarbonisation activities include the direct substitution of heat obtained from the combustion of fossil fuels and indirect actions for obtaining more efficient district heating systems. These indirect actions reduce costs and increase revenues, thereby improving the competitiveness of district heating.

Our approach has been to focus on real possibilities that have entered or are close to entering European district heating systems. Instead of collecting and assessing all interesting research opportunities, we focused on experiences from early adopters where companies have already taken the initial risk of using a new unconventional technology or method. The scientific literature concerning district heating presents many opportunities and suggestions; however, these must be assessed both technically and economically before installations are made in real district heating systems. In our vocabulary, an opportunity becomes a possibility when a company decides to use an opportunity as an investment decision or seriously considers an investment proposal. These possibilities identified in this report should become the backbone in district heating systems of the EU's goal of achieving a reduction of carbon dioxide emissions by 55% compared to 1990 levels by 2030.

To prove that these possibilities really exist, cases of implemented, planned, and proposed possibilities are presented in conjunction with each possibility. Because of the limited space in this report, the case descriptions are short and omit basic details. We provide relevant literature references and digital links for curious readers. References are used for documented research results, while links are used for news releases, ongoing projects, and company information.

The two following definitions are vital in the context for this research report.

P**ossibilities** for the decarbonisation of district heating systems have been implemented, planned, or proposed by early adopters, either inside or outside the district heating sector.

Cases are presented as evidence that possibilities can be implemented in district heating systems.

The role of possibilities and cases in this report is further elaborated in Section 1.3.

1.2 THE CURRENT SITUATION

Globally, district heating systems are still dominated by the combined heat and power (CHP) synergy and some heat recovery from waste-to energy plants (Gadd, 2012, Werner, 2017). CHP has been the main driver for district heating in societies based on fossil fuels. This synergy provides large amounts of heat, since thermal power plants have large heat losses from electricity generation. The basic conditions for the distribution and delivery of heat in traditional district heating systems are also based on the temperatures obtained from the combustion of fuels.

The development of the heat input to district heating systems over the last three decades is presented in Figure 1 for the current EU27 and in Figure 2 for the world. These two diagrams show that the decarbonisation process for the international district heating and cooling (DHC) sector has been very slow, especially globally.

Although the climate change issue has been in the global public awareness since the 1980s, very few countries have implemented strong policies and incentives for the reduction of fossil carbon dioxide emissions. The general policy attitude has been to postpone the decarbonisation of energy system by only stating long-term reduction ambitions, typically by 2050, rather than setting short-term goals for 2010, 2020 or 2030. Hence, the global community has already lost the initial opportunity to start the decarbonisation of energy systems in a smooth and calm manner over a longer period.

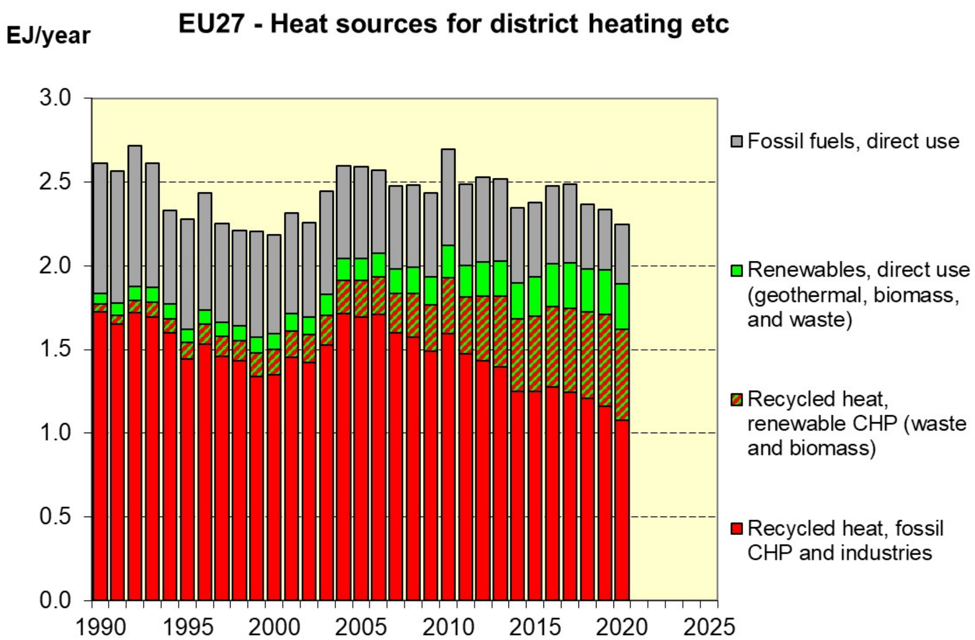

Figure 1. Heat supplied into all district heating systems in the current EU27 between 1990 and 2020, according to four different heat supply methods. Original data source: IEA World Energy Balances.

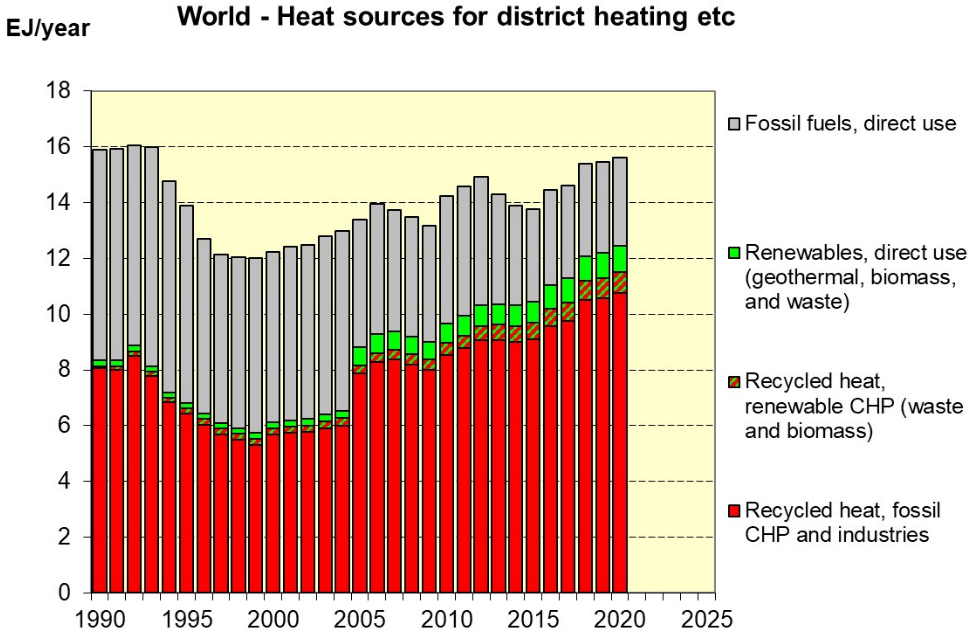

Figure 2. Heat supplied into all district heating systems in the world between 1990 and 2020, according to four different heat supply methods. Original data source: IEA World Energy Balances.

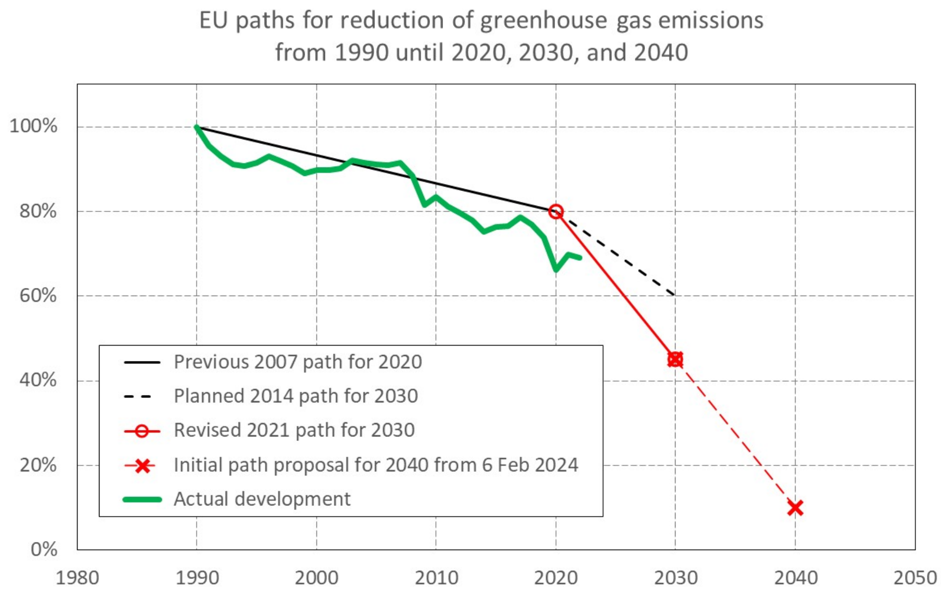

Figure 3. Five paths for the reduction of the EU carbon dioxide emissions since 1990.

In Europe, the transition towards decarbonisation of the DHC sector has now really started. The main decarbonisation driver within the European Union became the 2021 revised carbon dioxide reduction target for 2030, see Figure 3. Compared to the original 2014 plan for 2030 with a reduction of 40% compared to 1990, the new target became 55%. The implication from the 2021 revision became that the requested reduction rate during the 2020s increased with a factor of 1.75. Compared to the previous 2020 plan proposed in 2007, the annual reduction target for the 2020s increased by a factor of 5.25. Hence, European district heating systems will lose their largest heat provider once fossil CHP plants are closed. Some of them have already been closed, as indicated in Figure 1.

All energy sectors using fossil fuels in the EU have now to run concurrently much faster until 2030 concerning decarbonisation. This quick EU policy change (finally decided in June 2021) has created an avalanche of decarbonisation decisions in the EU, also within the DHC sector. We are likely to see companies competing for various decarbonisation technologies. Some chaos can be expected in this strong competition, since only six years remain until 2030. This is the congestion cost of not providing higher decarbonisation rates in Europe during the previous decades.

The current interest, momentum, and policy support surrounding district heating in Europe have never been so high since it was introduced more than a century ago. This supportive situation also applies to competing individual heat pump systems, although their market share in the European heat market is currently lower than that of district heating.

The growing European interest in district heating in recent years has also attracted more financial resources for district heating research. The available resources for EU projects concerning district heating are now almost one hundred times higher than they were twenty years ago. This change has initiated many innovations that challenge the traditional district heating technology for supplying, moving, and delivering heat. The traditional technology, which was originally developed in the fossil fuel context, has been critically examined against newer systems. Future district heating systems must be able to operate in other contexts, influenced by completely different future market conditions, including lower heat demand and non-fossil heat supply.

Many comprehensive European and even global survey reports have been written in recent years about district heating by researchers, consultants, trade organisations, and the European Commission. Some examples of these DHC market reports are:

- Nordic Heating and Cooling, (Patronen et al., 2017).
- The Tilia report concerning the integration of renewables and waste heat into DHC systems, (Galindo Fernández et al., 2021).
- The IRENA report concerning low-temperature renewables in DHC systems, (Bertelsen et al., 2021)
- The special district heating report (Volt et al., 2022) within the Clean Energy Technology Observatory (CETO) initiative, (Georgakaki et al., 2022).
- The extensive Tilia overview of European DHC markets, (Bacquet et al., 2022c, Bacquet et al., 2022d, Bacquet et al., 2022a, Bacquet et al., 2022b).
- The German study ‘Potenziale für UrbanTurn’, (Hay et al., 2022).
- The Euroheat & Power overview of support activities and projects of the European Commission on district heating and cooling, (Celsius and Euroheat & Power, 2023).

- The Euroheat & Power outlook concerning DHC markets, (Euroheat & Power, 2023a)

Some very interesting decarbonisation projects have also taken place in North America, while fewer decarbonisation initiatives have been undertaken in China and Russia, which are home to the two largest national DHC sectors in the world. Thus, the main conclusion from this introduction concerning the current DHC situation is that the European Union has become the global excellence centre for the transformation of district heating technology for supplying, moving, and delivering low-carbon heat.

1.3 ORGANISATION OF THIS PROJECT

1.3.1 Information sources

Recent possibilities concerning direct and indirect decarbonisation activities have been identified by continuously scanning several news sources concerning district heating and cooling during 2022 and 2023:

- Newsletters from international organisations, such as the International Energy Agency (IEA), the International District Energy Association (IDEA), Euroheat & Power (EHP), the EHP platform for DHC research (DHC+), the European Council for an Energy Efficient Economy (ECEEE), and the European Geothermal Energy Council (EGEC).
- National newsletters from national trade organisations, such as *Dansk Fjernvarme* in Denmark, *Energiföretagen* in Sweden, and *Warmtenetwerk* in the Netherlands.
- International trade magazines, such as *District Energy* from North America, the German and English versions of *EuroHeat & Power*, and *HotCool* from the Danish Board of District Heating (DBDH).
- National trade magazines, such as *Fjernvarmen* in Denmark and *Energi, Bioenergi, Kyla&Värme* and *Energi&Miljö* in Sweden

1.3.2 Database for input collection

A database was used as an intermediate tool for collecting and for managing information from the sources used in this project. Relevant possibilities and cases together with their associated references were compiled in the database using the following twelve labels:

- Part in the overall district value chain
- Main additional keyword
- Information type (case, possibility, or reference)
- Cases presented in the final report
- Status for each case (implemented, planned or proposed)
- Possibility affiliation
- Case initiator
- Case location
- Case country
- Documentation source

- Internet link concerning cases and references
- Initiator in the author group

1.3.3 Chapters: Value chain activities

The possibilities are presented in different chapters according to the associated activities in the district heating value chain, from heat usage to heat recycling or heat generation. The chosen activities are **using heat, connecting customers, moving heat, storing heat, removing carbon dioxide, and supplying heat into distribution networks**. The supplied heat activities were divided into three groups, based on the three main characteristics of heat supply: **linear renewable supply, heat recycling,** and **meeting peak demands.** This grouping of possibilities provided eight fundamental possibility groups that are defined and further presented in Section 1.4.

1.3.4 Chapter sections: Possibilities

In each chapter, the possibilities are presented in sections using second-level headings. Each chapter ends with a concluding second-level heading that introduces a summary of the chapter's key findings concerning implications, decarbonisation links, and brief assessments.

In our comprehensive review of decarbonisation possibilities for district heating, we applied the following limitations:

- We set a threshold of 70 decarbonisation possibilities due to limited time and research funds available for the project.
- We focused only on unconventional technologies and methods. Hence, we did not assess traditional district heating technologies or topics, such as CHP plants, biomass usage, waste incineration, prefabricated district heating pipes, or space heating technologies.
- Traditional district cooling systems were not considered; however, district cooling was included when a possibility concerned combined heating and cooling (CHC).
- We did not include longer-term possibilities to be implemented after 2030, since our aim was to present possible implementations before 2030.

1.3.5 Chapter sub-sections: Cases

The cases are presented in in the possibility sections under third level headings. The cases are presented according to their status. Three case labels are used for this purpose: implemented, planned, and proposed. An implemented case is a case where the real version of the possibility existed when this report and the corresponding database were finalised at the end of 2023; a planned case had an investment decision already made; a proposed case was waiting for an investment decision or was rejected by not receiving an investment decision. Implemented cases are always presented first, followed by planned and proposed cases. All implemented cases have the implementation year included at the beginning of their third level heading. Planned and proposed cases do not have these years in their headings, since they have not yet been implemented. Instead, these headings are marked with 'Planned' or 'Proposed'.

Concerning cases, the following two limitations must be acknowledged:

- We mainly considered European cases and a few North American and Chinese examples. The European context was chosen for promoting vital information about interesting cases to cross national borders. However, Swedish cases dominate, since the author group is affiliated with a Swedish university and is more familiar with these systems.

- The presented cases are just examples of each possibility. The reader should not view these examples as complete lists of implemented, planned, or proposed cases.

1.3.6 Aggregated findings

The aggregated findings concerning the cross-cutting possibilities of **degrees of freedom, temperature levels, heat pumps, digitalisation, supply responsibilities, institutional frameworks,** and **digital planning models** are presented and discussed in Chapter 10, which acts as the overall summary and discussion chapter in this report. The summary of the key findings is presented in Section 10.8.

1.3.7 Aggregated conclusions

The major conclusions from this inventory of early decarbonisation initiatives are reported in Chapter 11. The context for our conclusions can be summarised by the following three research questions:

- What kind of **decarbonisation activities** have been implemented, planned, and proposed in district heating systems?
- In what ways do **decarbonisation possibilities** differ from traditional district heating with a heat supply of fossil fuel origin?
- What are the **common denominators** for early decarbonisation projects in district heating systems?

The report does not provide conclusions concerning:

- Aggregated quantifications of reduced carbon dioxide emissions or amounts of heat obtained from the identified heat supply possibilities.
- Future development and economic assessments for the identified possibilities.
- The original assessments of the identified possibilities, which were performed by the owners of the case projects. For each case, the original assessment depended on various national and local conditions, and so the assessments varied by location.

1.4 DEFINITIONS OF THE 70 POSSIBILITIES

The 70 possibilities included in this report are briefly defined and described in the following nine sub-sections according to each possibility group.

1.4.1 Using heat (Chapter 2)

The using heat chapter presents possibilities that appear in customers' heating systems beyond the interface with the heat distribution network.

The eight possibilities based on using heat include additional heat deliveries, heat demands having higher temperatures than normally delivered by district heating networks, traditional demand temperatures, and the customers' ability to use lower radiator temperatures.

The decarbonisation options associated with using heat include substituting fossil fuel usage with alternative heat usage for connected customers, achieving a more efficient usage of delivered heat, and facilitating lower temperatures in heat distribution networks.

Possibility sections for using heat	Short explanation of each possibility
2.1 Tracking customer heat load variations	Tracking customer heat loads by estimating their daily heat load patterns
2.2 Tracking deviations in heat usages	Tracking deviations in heat usages by identifying abnormal user behaviour
2.3 Biogas from district heating	Heat delivery for heating the biogas process to avoid using own biogas for this purpose, providing higher customer output of manufactured biogas
2.4 Food supply chain	Heat delivery to the food supply chain
2.5 Steam from district heating	Heat delivery to heat pump for making steam
2.6 Temperature boosting	Heat delivery with higher temperature obtained by heat pump
2.7 Tracking customer temperatures	Tracking customer demand temperatures
2.8 Tracking radiator systems by thermal lengths	Tracking the status of customer space heating systems by estimating the equivalent thermal lengths

1.4.2 Connecting customers (Chapter 3)

The connecting customers chapter presents possibilities that appear in the interface between the heat distribution network and the customers' heating systems. This interface is often called a 'substation', although the term 'energy transfer station' is also used in some countries.

The six possibilities concerning connecting customers comprise a special customer interface for flats, the local reduction of the return temperature from a substation, classification of deviations in substations, and tracking substation behaviours.

The main decarbonisation option associated with connecting customers is achieving a more efficient usage of heat, such as by using lower temperatures in customers' heating systems.

Possibility sections for connecting customers	Short explanation of each possibility

3.1 Flat substations	Modified customer interface that manages heat delivery to each flat in new multi-family buildings
3.2 Local reduction of the return temperature	Reduced return temperature from a substation by using a heat pump
3.3 Fault standardisation in substations	Faults in substations are standardised to monitor their frequency and the behaviour of typical deviations in substations
3.4 Supervision of substations	High-resolution measurements are gathered from substations
3.5 Tracking deviations in substations	Deviations in substations are tracked from high resolution measurements
3.6 Tracking thermal lengths in heat exchangers	Thermal lengths are estimated from high resolution measurements to identify fouling in heat exchangers used in substations

1.4.3 Moving heat (Chapter 4)

The moving heat chapter presents possibilities that appear in heat distribution networks.

The twelve possibilities concerning moving heat include six different network configurations, the use of plastic pipes, decentralised heat supply, tracking the by-passes or shortcuts that create unwanted circulation flows, the central reduction of the aggregated return temperature, and automated oxygen and corrosion monitoring.

The main decarbonisation option associated with moving heat is achieving a more efficient heat distribution, such as by using of lower temperatures in heat distribution networks.

Possibility sections for moving heat	Short explanation of each possibility
4.1 Classic configurations	Traditional configurations in heat distribution with one supply pipe and one return pipe together with a circulation flow from the supply pipe to the return pipe when required
4.2 Modified classic configurations	Modifications of the classic configuration for using lower supply and return temperatures compared to traditional classic configurations
4.3 Multi-level configurations	More than one supply temperature is applied in a heat distribution network
4.4 Ultra-low configurations	Cold networks are used for heat delivery, since the supply temperatures are lower than 50°C
4.5 Cold CHC configurations	Applying combined heating and cooling in a cold network, by using the warm pipe for space heating, while the cold pipe is used for space cooling
4.6 Warm CHC configurations	Applying combined heating and cooling in two separate networks, by extracting heat from a district cooling network and supplying this heat to a district heating network

4.7 Plastic pipes	Using plastic pipes in low-temperature heat distribution networks
4.8 Decentralised feed-in	Decentralised heat supply in a district heating network
4.9 Tracking circulation flows	Tracking the magnitude of the annual circulation flow in a heat distribution network
4.10 Central reduction of the return temperature	Central reduction of the return temperature by using a heat pump
4.11 Automated oxygen measurement and removal	Continuous measurement and removal of oxygen in a heat distribution network
4.12 Automated corrosion measurement	Continuous measurement of corrosion in a heat distribution network

1.4.4 Storing heat (Chapter 5)

The storing heat chapter presents possibilities that appear when heat storage is employed in district heating systems for breaking the time dependence between heat supply and heat delivery.

The nine possibilities concerning storing heat comprise different methods for achieving heat storage, mostly by using water as the storage liquid.

The main decarbonisation option associated with storing heat is achieving a more efficient heat supply to break the time dependence between heat supply and heat delivery.

Possibility sections for storing heat	**Short explanation of each possibility**
5.1 Aquifer storages	Storing heat in deep geothermal water basins
5.2 Borehole storages	Storing heat in shallow boreholes in the ground
5.3 Mine storages	Storing heat in abandoned water-filled mines
5.4 Tank storages	Storing heating in vertical water-filled tanks, installed on the ground or buried in the ground
5.5 Pit storages	Storing heat in water-filled pits excavated into the ground
5.6 Rock cavern storages	Storing heat in water-filled rock caverns
5.7 Heat distribution pipes	Storing heat in heat distribution pipes by slightly altering supply temperatures
5.8 Buildings	Storing heat in building structures by slightly altering the indoor temperature setpoints
5.9 Other storages	Storing heat by other storage methods

1.4.5 Removing carbon dioxide (Chapter 6)

The removing carbon dioxide chapter presents possibilities that appear when carbon dioxide removal (CDR) is used to remove carbon dioxide emissions.

The three possibilities concerning removing carbon dioxide comprise its removal after the combustion of biomass and waste, and the removal of fossil-based plastics before combustion in waste incineration plants.

The decarbonisation associated with removing carbon dioxide include the removal of carbon dioxide from the natural coal cycle and preventing carbon dioxide emissions from the combustion of fossil-based plastics in waste-to-energy plants.

Possibility sections for removing carbon dioxide	**Short explanation of each possibility**
6.1 CDR from biomass CHP	Extracting carbon dioxide from flue gases emitted from the combustion of biomass
6.2 CDR from waste-to-energy	Extracting carbon dioxide from flue gases obtained from waste incineration
6.3 Plastic recycling before waste incineration	Avoiding carbon dioxide emissions by removing waste plastics before waste incineration

1.4.6 Supplying heat: Linear renewable supply (Chapter 7)

The linear heat supply chapter considers possibilities when linear heat supply chains are applied to meet base load demands. These possibilities are not associated with heat recycling, but with renewable heat sources.

The nine possibilities concerning linear heat supply chains comprise five ways of extracting geothermal heat and four possibilities for the direct use of solar heat, excess electricity, and ambient heat from water and air.

The main decarbonisation option associated with linear heat supply chains is the direct substitution of fossil-based heat supplies with renewable heat sources and ambient heat, which eliminates fossil carbon dioxide emissions.

Possibility sections for linear heat supply chains	**Short explanation of each possibility**
7.1 Geothermal heat from volcanic zones	Heat extraction from deep geothermal wells located close to major cracks in the earth's crust
7.2 Geothermal heat from aquifers	Heat extraction from deep geothermal water basins below the ground, sometimes by using heat pumps
7.3 Geothermal heat from crystalline bedrocks	Heat extraction from a deep crystalline bedrock below the ground, sometimes by using heat pumps
7.4 Geothermal heat from closed mines	Heat extraction from closed mines by using heat pumps
7.5 Geothermal heat from shallow grounds	Heat extraction from the ground close to the surface by using heat pumps
7.6 Solar district heating	Heat generation from solar thermal collectors

7.7 Electric boilers	Heat generation from electricity, mostly obtained from wind power
7.8 Ambient heat from sea and lake water	Heat extraction from ambient sea and lake waters by using heat pumps
7.9 Ambient heat from air	Heat extraction from ambient air by heat pumps

1.4.7 Supplying heat: Heat recycling (Chapter 8)

The heat recycling chapter presents possibilities that appear when heat recycling from external excess heat sources is applied.

The thirteen possibilities concerning heat recycling comprise biorefineries, hydrogen generation and usage, petrochemical plants, electricity transformers, new industrial processes, six different combined heating and cooling options, and low-temperature heat from sewage waters.

The main decarbonisation option associated with heat recycling is direct substitution of fossil-based heat supply with recycled heat, which eliminates fossil carbon dioxide emissions.

Possibility sections for heat recycling	**Short explanation of each possibility**
8.1 Fuel refineries	Heat recycling from refineries that produce non-fossil transport fuels
8.2 Hydrogen generation providing excess heat	Heat recycling from electrolysers that generate hydrogen from electricity
8.3 Hydrogen usage in CHP plants	Heat recycling from hydrogen-fuelled CHP plants
8.4 Petrochemical plants	Heat recycling from petrochemical plants
8.5 Electricity distribution	Heat recycling from equipment in electricity distribution networks
8.6 New industrial processes	Heat recycling from new decarbonised industrial processes
8.7 Centralised district cooling	Heat recycling from space cooling in district cooling networks by using centralised heat pumps
8.8 Decentralised district cooling	Heat recycling from space cooling in cold networks by using decentralised heat pumps
8.9 Air-cooled data centres	Heat recycling from air-cooled data centres
8.10 Water-cooled data centres	Heat recycling from water-cooled data centres
8.11 Battery manufacturing	Heat recycling from the manufacturing of electric batteries
8.12 Food supply chain	Heat recycling from the food supply chain
8.13 Sewage water	Heat recycling from sewage water treatment plants

1.4.8 Supplying heat: Meeting peak demands (Chapter 9)

The peak supply chapter presents possibilities for meeting peak heat demands from customers during cold days, which increase the demand for additional heat supply.

The three possibilities for meeting heat peak demands are using non-fossil fuels in traditional boilers, large heat storage solutions, and demand side management.

The decarbonisation options associated with meeting peak demands include direct substitution of fossil-based heat supplies with non-fossil heat sources, the use of heat storages, and temporary heat supply deficits. All these activities eliminate fossil carbon dioxide emissions for peak supply.

Possibility sections for meeting peak demands	**Short explanation of each possibility**
9.1 Non-fossil fuels	Meeting peak demands by using non-fossil boilers
9.2 Large heat storages	Meeting peak demands by using large heat storage solutions
9.3 Allocation of heat supply deficits	Meeting peak demands through the fair allocation of heat supply deficits

1.4.9 Value chain (Chapter 10)

The value chain manages the heat flow initially coming from the heat outputs of the supply units and the carbon dioxide removal units. The heat flow can then utilise the heat storages for breaking the time dependence between demand and supply. The next steps will be the heat movement in pipes and the heat transfer in the customer substations. The value chain ends with the final heat usage in the customer buildings. By focussing on cross-cutting issues for the whole value chain, the silo approach used in the previous fundamental chapters is left behind.

This value chain chapter presents aggregated possibilities that appear in seven strategy groups concerning the value chain. These seven possibilities comprise

- degrees of freedom for possibility options
- suitable temperatures in heat distribution networks
- heat pumps for solving mismatches between low supply temperatures and high demand temperatures
- digitalisation options for supervision and fault detection
- supply responsibilities
- institutional frameworks that set the market conditions for district heating at the international, national, regional, and local levels
- digital planning models for the efficient aggregation of local conditions at the regional and national levels

The main decarbonisation options associated with the value chain are methods for planning and organising efficient district heating systems and societal support measures for promoting fossil-free district heating systems.

Possibility sections for the value chain	Short explanation of each possibility
10.1 Degrees of freedom	Various ways of using degrees of freedom in the district heating value chain
10.2 Temperature levels	Various ways of using different distribution temperatures
10.3 Heat pumps	Various ways of using heat pumps in the district heating value chain
10.4 Digitalisation	Various ways of using digitalisation in the district heating value chain
10.5 Supply responsibilities	Various ways of using supply responsibilities in the district heating value chain
10.6 Institutional frameworks	Opportunities and barriers in the district heating value chain related to international and national legislations, rules and support schemes
10.7 Digital planning models	Various ways of using open data for planning new or extended district heating systems

1.5 OVERVIEW OF THE IDENTIFIED POSSIBILITIES AND CASES

As described in Section 1.3, a database was used for collecting and managing information to prepare the possibilities and cases presentations in this report. The finalised database contain 85 possibilities, 361 cases, and 147 references. However, following a downsizing process, 70 possibilities and 284 cases have been included in this report. Hence, a discrepancy exists between the number of possibilities and cases in the database and the report. These discrepancies are reported by chapter in Table 1 and Table 2. District cooling in the penultimate row in both tables was initially intended to be a separate focus area but was eliminated in the downsizing process to reach the threshold of 70 possibilities.

An overview of the locations of the cases in the database is provided in Figure 4.

Table 1. Number of possibilities included in the database and this report.

	Included in the database	Included in this report	Not included in this report
Chapter 2 - Using heat	10	8	2
Chapter 3 - Connecting customers	6	6	
Chapter 4 - Moving heat	21	12	9
Chapter 5 - Storing heat	9	9	
Chapter 6 - Removing carbon dioxide	4	3	1
Chapter 7 – Linear renewable supply	9	9	
Chapter 8 – Recycling heat	13	13	
Chapter 9 – Meeting peak demands	3	3	
Chapter 10 - Value chain	7	7	
District cooling	3		3
Total	85	70	15

Table 2. Number of cases included in the database and in this report.

	Included in the database	Included in this report	Not included in this report
Chapter 2 - Using heat	22	16	6
Chapter 3 - Connecting customers	14	12	2
Chapter 4 - Moving heat	53	32	21
Chapter 5 - Storing heat	39	36	3
Chapter 6 - Removing carbon dioxide	22	18	4
Chapter 7 - Linear heat supply	77	62	15
Chapter 8 - Recycling heat	96	72	24
Chapter 9 – Meeting peak demands	11	10	1
Chapter 10 - Value chain	26	26	
District cooling	1		1
Total	361	284	77

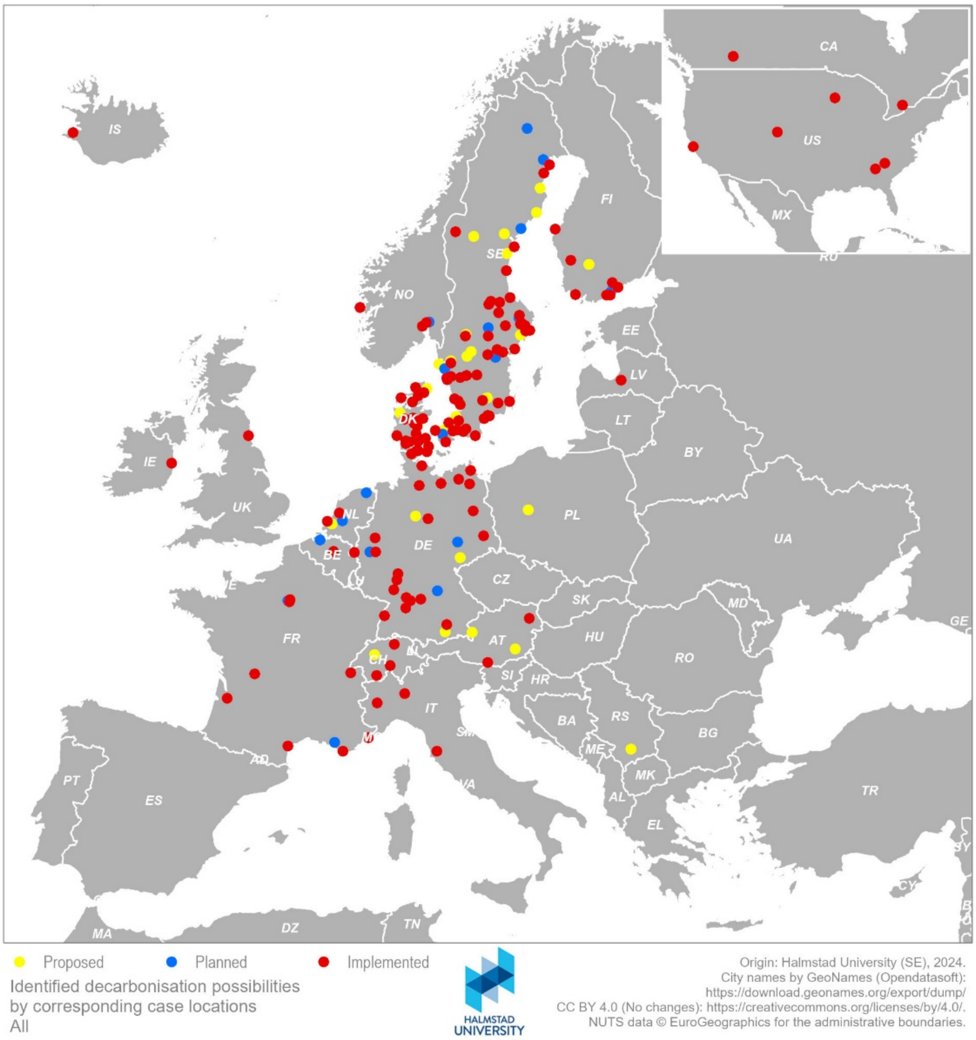

Figure 4. Map showing the locations of cases in the database concerning all parts of the value chain.

1.6 NOTIFICATIONS

The author group appreciated feedback from the Energiforsk-Futureheat steering committee during the application process and feedback during the writing process from the reference group for this project. An early version of this report was also assessed during 2023 by a wider external group of reviewers outside the reference group. We appreciate valuable feedback from Bengt-Göran Dalman, Dag Henning, Henrik Näsström, John Johnsson, Thore Sahlin, Jens Brage, Raziyeh Khodayari, Lieve Helsen, Erik Axelsson, and Patrik Grönbeck in this external reviewer group.

This report provides a compact overview of a dynamic, intense, and ongoing process for decarbonisation of district heating systems containing information about both companies and projects. Recent changes of companies and projects between 31 December 2023 (being the final date for news input) and 30 April 2024 (being the final project date) have in general not been recognised, but some exceptions have been included.

2 Using heat

The eight identified possibilities concerning using heat, according to Subsection 1.4.1, include tracking customer load variations, deviations in heat usages, additional heat deliveries to the food supply chain, higher demand temperatures than normally delivered in district heating networks, traditional demand temperatures, and the customers' abilities to use lower radiator temperatures.

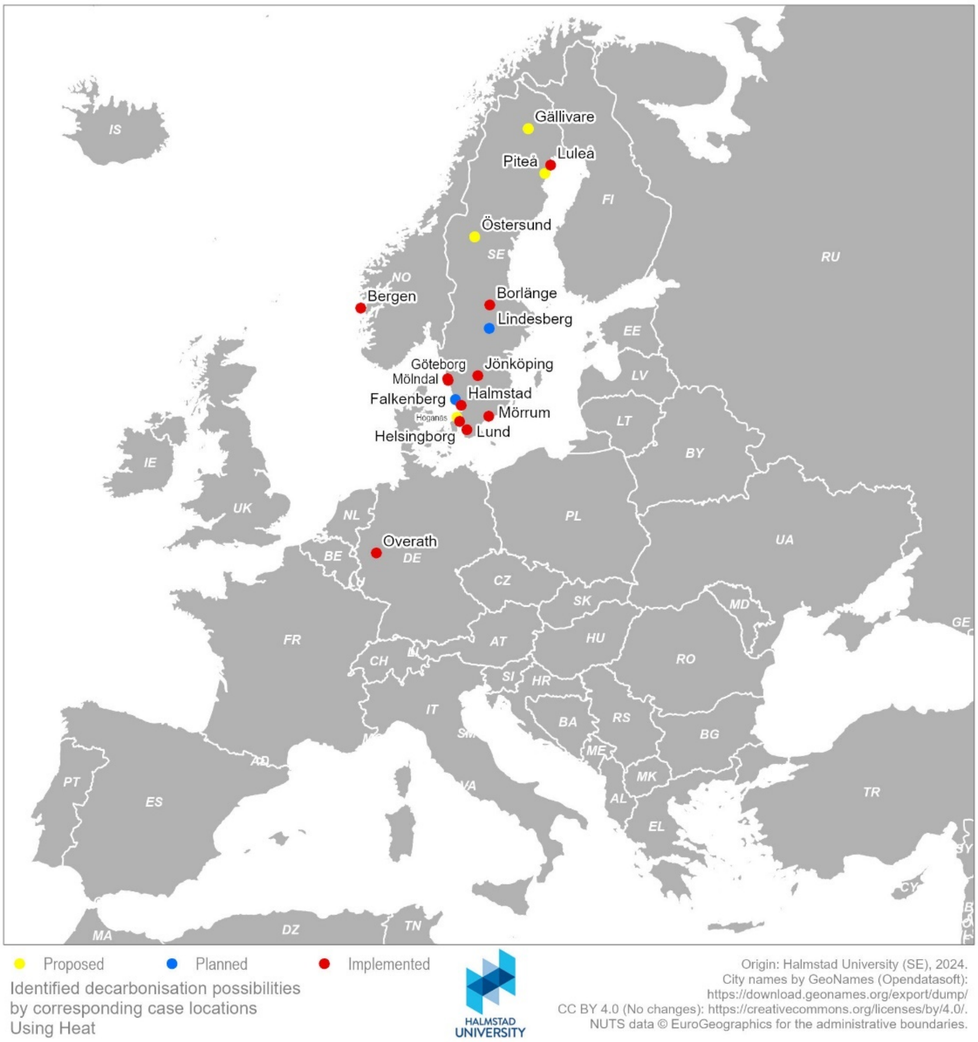

Figure 5. Map showing locations of identified cases in the database concerning using heat.

2.1 TRACKING CUSTOMER HEAT LOAD VARIATIONS

To track customer heat load variations in district heating, it's crucial to understanding of the customer's weekly heat load patterns. Traditional estimates based on a few measurements are not always enough since each building is unique when it comes to heat load patterns. This is because of the different kinds of buildings operation and buildings properties, but also because a what building is used for is shifting over time.

2.1.1 2019: Öresundskraft, Helsingborg-Ängelholm, Sweden

SeMI was a research project financed by the KK-foundation that was carried out at Halmstad University. It involved compiling and using data from 1222 buildings with a total floorspace of 3.4 million m^2 and 430 GWh of heat use in 2016. The aim of using various data mining applications was to find a structure for the effective management of the overall district heating network and to understand behaviour.

The study identified a way of diversifying time laps weekly and for weekends for the heat use in the findings of tracking customer heat loads. A data-driven approach for automatic heat load pattern detection was used for determining behaviours in six different customer categories which can be used to describe the entire network in Sweden and other countries. The categories were 1. Multi-dwelling buildings; 2. Commercial buildings; 3. Public administration buildings; 4. Health and social buildings; 5. School buildings, and 6. Industrial buildings. From the data set 16 main groups of heat load patterns was determined. A 17:th group contined "outliers". An interesting finding was that the outlier group mainly contain buildings with unique heat load patterns rather than fault data points. In other words, the outlier is not equal to faulty!

Reference: (Calikus et al., 2019)

2.2 TRACKING DEVIATIONS IN HEAT USAGE

One of the most common ways to identify faults in heat use is to analyse heat power signatures manually. When using automated methods, it is a difficult to differentiate between faults and outliers. In response to this difficulty a method to reduce false faults detection is presented with a single case.

2.2.1 2018: Öresundskraft, Helsingborg-Ängelholm, Sweden

Researchers from Halmstad University proposed a novel method for identifying abnormal, or deviating, heat demand using a robust regression with datasets from smart meter readings in 1700 district heating heated buildings in Helsingborg and Ängelholm in south-west Sweden. Öresundskraft has provided the data sets. Ordinary Least Squares (OLS) is a typical approach to estimate energy signatures. Alternatively, a Radom Sample Consensus (RANSAC) algorithm can be used. RANSAC is a robust approach for parameter estimation with a high degree of accuracy even when a significant number of outliers are present in the data set. Setting the ratio to 20% when fitting the regression line, the statistical metric R^2 result that the RANSAC method has higher goodness-of-fit score of 61% for all heat power signatures. This is significantly higher than the estimates obtained by OLS. Compared to the state-of-the-art outlier-based approach this novel dispersion-based and aggregated method is significantly more efficient in defining thresholds to prevent outliers from going unspotted and limit false alarms.

Reference: (Calikus et al., 2018)

2.3 BIOGAS FROM DISTRICT HEATING

Using district heating instead of biogas for internal sanitation and heating the process in biogas production would increase the amount of biogas available for other applications. Hence, additional biogas would become available as a renewable fuel to power vehicles. Thus, vehicles can be indirectly powered by district heating.

An average Swedish sewage water treatment plant can increase the output of biogas by 1.35 to 2.1 GWh annually, which is in line with the NSVA case presented below.

Two cases with different feedstocks are presented below. The difference in heat supply per GWh of biogas between the two cases is due to the different feedstocks that are used.

Reference: (Lundqvist, 2009)

2.3.1 2019: Biond, Helsingborg, Sweden

Biond is a biogas producer, and one of its two sites is in Helsingborg. The annual production is 70–80 GWh of raw gas. Since the raw materials are biological leftovers from households, restaurants, and slaughterhouses, it is necessary to increase the sanitisation temperature to 70°C. This heat is supplied by district heating with a supply temperature of 80°C and a return temperature of 70°C. The annual supply from district heating is about 6 GWh. The biogas process is mesophilic, which means the temperature in the reactor must be around 37°C. The sanitation treatment of the substrate is enough to achieve the temperature needed for the mesophilic process. The plant also delivers about 145,000 tonnes of biofertiliser annually.

This case is on the same site as case 4.1.3.

Link:
https://www.biond.se/anlaggningar/

2.3.2 2007: NSVA, Helsingborg, Sweden

NSVA is a freshwater supplier and operates wastewater treatment plants for eight municipalities in northwest Scania. The substrate is sewage water sludge from the municipal sewage water system in Helsingborg, with the sewage water equivalent to a population of 170,000. The annual biogas production is 10 GWh. The process is mesophilic (37°C) and is heated from district heating, requiring 3 GWh annually. The plant also uses 1 GWh of district cooling and 1.8 GWh of electricity. The demands concerning the plant’s products include raw gas production and upgrading the gas to vehicle gas.

Reference: Personal communication with NSVA.

2.4 FOOD SUPPLY CHAIN

This possibility is to use excess heat from various sources to deliver heat for food production in greenhouses. As a result, the fossil fuels currently being used for food production can be substituted with recycled heat.

An international overview of early implementations of using excess heat for heating greenhouses is provided by (Nilsson and Nimmermark, 2013). Examples of local assessments for using this possibility have been provided by (Markström and Emelie, 2014) and (Persson et al., 2020a). Internationally, some interest has also been shown in using geothermal heat for agricultural purposes (IRENA, 2022).

2.4.1 2012: Elleholm, Mörrum, Sweden

The Elleholm greenhouses in Mörrum, next to Karlshamn, have been using excess heat from the Södra Cell paper pulp plant in Mörrum since 2012. The excess heat is delivered by the Karlshamn district heating system. The main output from the 60,000 m^2 of greenhouses is tomatoes.

Links:
https://elleholmstomater.se/miljo/
https://www.ja.se/artikel/50703/vi-mste-srskilja-oss.html
https://bioenergitidningen.se/fossilanvandningen-har-minskat-med-83-procent-sedan-2002/

2.4.2 2023: Luleå, Sweden

Luleå Energi in northern Sweden has implemented a minor pilot project by using district heating for food production. Located in the city harbour, tomatoes and some herbs are provided for a local restaurant. The heat is delivered from one of the return pipes in the district heating system.

Links:
https://www.energi.se/artiklar/2023/mars-2023/luleas-smarta-vaxthus-drivs-med-returvarme/
https://www.luleaenergi.se/hallbarhet/miljomassig-hallbarhet/vaxthuset/

2.4.3 Planned: Regenergy Frövi, Sweden

Regenergy Frövi is a planned project with an investment decision already made. The site is expected to be commissioned in April 2024. It will recover 50 GWh of heat annually from the Billerud paper mill that produces carton boards and liquid packaging boards. The heat will be used in a large 100,000 m^2 greenhouse close to the paper mill to obtain 8,000 tonnes of tomatoes per year. The food production coordinator, the WA3RM company, has a 20-year contract for using the excess heat. The operation of the greenhouse will be managed by Local Harvest, a Dutch company. The original plan for the site also included the breeding of large shrimps, however, this proposal was later rejected for environmental reasons.

This project is now the Swedish case included in the international Coralis project, having replaced a similar project that was proposed but then rejected in Höganäs. Coralis is a broad EU project lasting between 2020 and 2024 that concerns the implementation of industrial symbiosis in energy-intensive industries. Three case projects are included in this implementation project; the other two projects, which are located in Italy (Brescia) and Spain (Cartagena), have no affiliation with food production.

Links:
https://www.wa3rm.com/
https://www.wa3rm.com/regenergy-frovi
https://www.energi-miljo.se/spillvarme-for-tomater-men-inga-rakor/
https://www.energi-miljo.se/snart-odlingsstart-i-spillvarmda-vaxthuset/
https://www.dn.se/ekonomi/brister-i-sveriges-livsmedelsberedskap-jatterakor-och-tomatodling-en-del-av-losningen/
https://cordis.europa.eu/project/id/958337
https://www.coralis-h2020.eu/
https://www.coralis-h2020.eu/lighthouses/lighthouse-hoganas/

2.4.4 Proposed: Regenergy Gällivare, Sweden

In conjunction with the expected implementation of the HYBRIT steel process, this proposal suggests major heat recovery for food production. The HYBRIT process is a new way of manufacturing fossil-free ‘green’ steel by using hydrogen instead of coal, which is currently used in most steel processes.

This innovative development project is a cooperation between LKAB, SSAB, and Vattenfall. The main goal is to recycle excess heat from the HYBRIT site and transfer it to the district heating system in Gällivare. The next step is to provide heat for food production. The coordinator of the idea of recycling heat for food production is the WA3RM company. The heat recovery process is still in its design phase, which is expected to end in 2027. Essential conditions, such as the location and the type of food production, are not yet finalised.

Links:
https://www.hybritdevelopment.se/en/
https://gallivare.se/Kommun/Nyheter/Gallivare-staller-med-hjalp-av-spillvarme-om-till-ett-hallbart-samhalle/
https://www.wa3rm.com/regenergy-gallivare

2.4.5 Proposed: Regenergy Östersund, Sweden

In conjunction with the second EcoDataCenter facility, this proposal suggests recovering low-temperature excess heat from the cooling process in this new data centre and using it for sustainable food production. The first phase of the project will provide 20 MW of electricity in 2026, with a planned expansion to 150 MW in 2033.

The heat recovery project is a cooperation between Jämtkraft (the district heating system operator in Östersund), EcoDataCenter, WA3RM, and the Östersund municipality. The heat recycling project is still in its design phase, which is expected to end in 2028. Essential conditions, such as the location and the type of food production, are not yet finalised.

Links:
https://ecodatacenter.tech/data-center/ecodatacenter-2
https://www.datacenterdynamics.com/en/news/ecodatacenter-plans-150mw-data-center-campus-%C3%B6stersund-sweden/
https://www.wa3rm.com/regenergy-ostersund
https://www.svt.se/nyheter/lokalt/jamtland/eco-data-center-etablerar-sig-i-ostersund-spillvarmen-ska-ga-till-matproduktion

2.5 STEAM FROM DISTRICT HEATING

In some industry sectors, steam is commonly used. Due to the high temperatures needed in industry, steam is mainly produced with fossil fuels. An alternative is to use district heating in combination with high-temperature heat pumps (HTHPs) or very high-temperature heat pumps (VHTHPs), which can raise temperatures from below 100°C to up to 100°C (HTHPs) or over 150°C (VHTHPs). Two cases are presented: one is from the medical industry, and the other is a manufacturer of heat pumps for high temperatures.

Reference: (Tveit et al., 2021)

2.5.1 2017: Olvondo, Mölndal, Sweden

AstraZeneca in Mölndal, Sweden, started out using fossil oil and switched to natural gas in 1997. It then switched to biogas in 2018 to produce steam with a low-carbon fuel. The upgrade aimed to produce steam using high-lift heat pumps as part of a more efficient, more robust, less expensive, and overall more sustainable solution. Steam at 1 MPa and 183°C is produced using a VHTHP. The heat source for the heat pumps is mainly excess heat from cooling compressors at around 40°C.

AstraZeneca's solution uses one of Norwegian Olvondo's high-lift heat pumps, which are based on a reversed Stirling engine design. The high-lift heat pump was installed at AstraZeneca's R&D centre in Mölndal in 2017. Industrial high-temperature heat pumps are now considered an important tool in AstraZeneca's sustainability efforts for reducing their carbon dioxide emissions.

Reference: (Zevenhoven et al., 2020)

Link:
https://highlift.olvondotech.no/olvondo-technology-promotional-video/

2.5.2 2023: SPHeat, Overath, Germany

SPHeat, a company that provides sustainable process heat solutions, has developed a series of high-temperature heat pumps for industrial process heat. Traditional industrial heat pumps have outlet temperatures below 100°C, yet most processes use temperatures in the range of 100 to 200°C; SPHeat's ThermBoosters can reach 165°C. This is achieved by using a high-temperature piston compressor with 400 kW to 1 MW per compressor in one or two stages in conjunction with innovative process technology. The heat source medium is a liquid or steam. Low-temperature excess heat (8 to 120°C) is thus converted to high-temperature process heat (165°C).

A gelatine factory and an industrial baker, among others, are using SPH's solutions. According to SPH, the global demand for industrial process heat is 6,500 TWh per year.

In 2023, two ThermBoosters provided high-temperature heat for UBQ Materials' biobased recycled plastic drying process. The raw material is unsorted household waste, including organic and non-recyclable materials. The thermoplastic is a circular solution that can be used as a sustainable replacement for plastic, wood, or concrete, thus reducing carbon dioxide emissions.

Links:
https://spheat.de/thermbooster/?lang=en
https://spheat.de/news/?lang=en
https://spheat.de/2023/06/02/delivered-the-first-two-thermbooster/?lang=en
https://spheat.de/neu/wp-content/uploads/2023/05/4141_Flyer_EN_1.pdf

2.6 TEMPERATURE BOOSTING

Many processes can deliver excess heat, but not necessarily at a temperature suitable for direct use for space heating and hot water in all buildings connected to a district heating system. The temperature can be too low for some or all buildings. Instead of using traditional systems that supply high-temperature heat directly to customers, the temperature can be boosted locally in buildings when the requested temperature exceeds the supplied temperature. Then, the optimisation of the system has one fewer limitation. This kind of cold network is often referred to as fifth-generation district heating.

Reference: (Buffa et al., 2019)

2.6.1 2020: LKF and Kraftringen, Lund, Sweden

The Xplorion building in southern Brunnshög in Lund, Sweden, has 54 flats and 4,374 m^2. The building is a passive house and has several smart solutions installed, including a heat pump supplied by DH, as shown in the figure below. The supply temperature can be changed between 35 and 65°C. The heat pump can run on electricity from the building's photovoltaic (PV) installation. The benefit of using the heat pump is that the building can be served with a 45°C flow temperature and still provide 50 to 60°C DHW at the tap.

Conventional hot water circulation systems in buildings use five pipes; Xplorion only uses three pipes. One pipe is for the supply of hot water for both DHW and heating; one is for the return water; and one is for cold tap water. Each flat has a heat interface unit (HIU) that provides DHW and heating close to the flat, allowing for lower temperatures in the radiators. The return temperature is also lower, thereby reducing heat losses in the grid. Xplorion's low heat usage makes it suitable for a connection to an ultra-low temperature district heating (u-LTDH) network. This solution is described in the Cool DH EU project. The utilised heat with low temperature is 163 MWh/year, resulting in 150 MWh/year in primary energy savings.

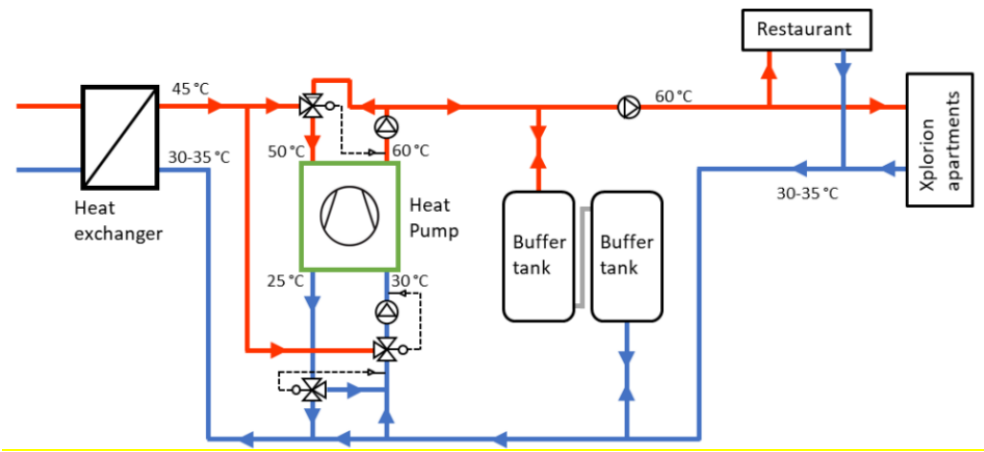

Figure 6. A simplified sketch of the temperature booster in the Xplorion heating system.

Reference: (Moallemi et al., 2023a)

2.7 TRACKING CUSTOMER TEMPERATURES

Temperature level issues on the primary and secondary sides in DH systems are increasing as buildings become more energy efficient with lower needs for high temperatures for space heating. Simultaneously, new kinds of heat sources are being introduced in DH systems, and the primary side is expected to mirror the secondary side. Attempts to track indoor supply and return temperatures from customers are still uncommon, although some analyses of surveys have been performed. The transition to lower operating temperatures in dwellings is gradually occurring as the use of fourth-generation district heating (4GDH) systems with low temperatures becomes more common.

2.7.1 2017: Poseidon, Gothenburg, Sweden

Temperature surveys and analyses of 109 radiator systems were conducted in multi-family buildings in five different parts of Gothenburg: Angered, Guldheden, north Hisingen, south Hisingen, and Frölunda. The data for 2015 was provided by Bostads AB Poseidon. The highest supply temperatures, slightly over 80°C, were found in Guldheden, which has one of the oldest building stocks in the survey. The average supply and return temperatures for a design outdoor temperature of -16°C were 64°C and 42°C, respectively. The supply and return temperatures of the surveyed radiator systems were calculated and presented for seven different outdoor temperatures. The results showed that large radiator heat transfer surfaces had the biggest potential for low operating temperatures, making them suitable for low-temperature district heating (LTDH).

An overview of estimated supply and return radiator temperatures at design outdoor temperature is presented in Figure 7 for 101 of the 109 radiator systems. The corresponding supply and return temperatures were obtained directly from the author, since they were not reproduced in the paper. It is evident from the figure that a considerable variation exists in applied radiator flows. Low flows provide wide differences between the supply and return temperatures and vice versa. Low flows provide also low return temperatures, giving essential conditions for low return temperatures in the flow back to the heat distribution network.

Reference: (Jangsten et al., 2017)

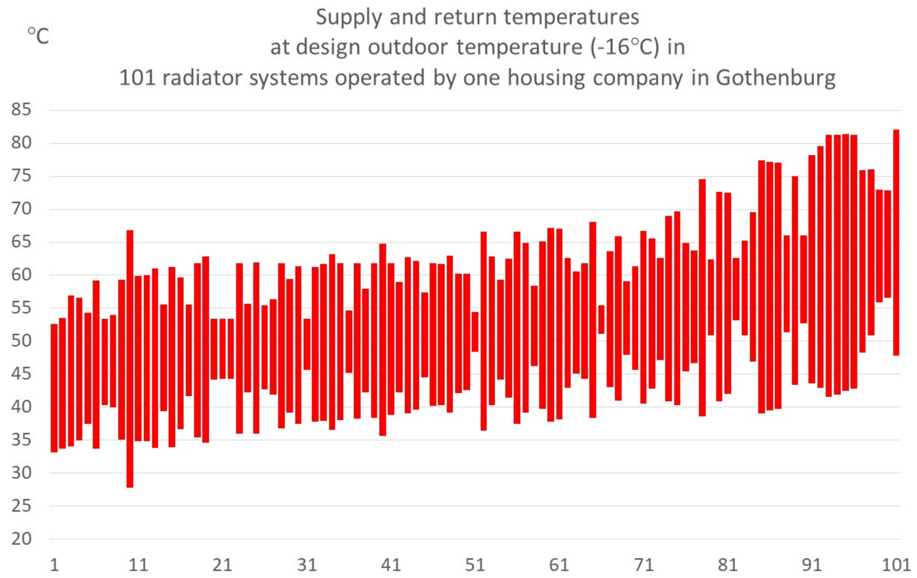

Figure 7. Estimated radiator temperatures at design outdoor temperature for 101 buildings according to the reference. The upper end of each bar provides the supply temperature, while the lower end provides the return temperature. The radiator systems have been sorted according to the average radiator temperature, presenting large radiators according to the heat demand to the left, while small radiators can be found to the right.

2.8 TRACKING RADIATOR SYSTEMS BY THERMAL LENGTH

This possibility involves a novel, simple, and quick method for estimating the effective relative size of the radiator system for each customer's heating system. It is based on the aggregated thermal length of the radiator system. The thermal length of a heat exchanger reflects its ability to transfer heat from the heating fluid to the heated fluid. It is also known as the number of transfer units (NTU) in heat exchanger textbooks and was formally introduced in the 1950s (Kays and London, 1955).

With a long-term ambition to lower heat distribution temperatures, district heating operators have an interest in identifying and eliminating barriers to reducing temperatures. Short thermal lengths may be due to either small heat-transferring surfaces or high radiator flows. High radiator flows are easy and cheap to solve via flow adjustment of the heating circuit. Conversely, a short thermal length due to small heat-transferring surfaces in a customer's radiator system is a long-term barrier to using lower network temperatures since it requires higher radiator temperatures in the customer's building. Hence, long thermal lengths in customers' radiator systems are essential to use lower temperatures in heat distribution networks.

The effective thermal length for a radiator system can be estimated for an hour, a day, or at the design temperature by using the aggregated supply and return temperatures for the heating fluid and the estimated indoor temperature for the heated fluid. The thermal length NTU can then be estimated as:

$$NTU = \ln((t_s - t_i)/(t_r - t_i))$$

t_s = aggregated supply temperature in the radiator system
t_r = aggregated return temperature in the radiator system
t_i = estimated indoor temperature

Three unpublished cases are presented below to show how this proposed method can support district heating companies in achieving low distribution temperatures. The first case reveals how the thermal length can vary within a group of multi-family residential buildings, while the two other cases show the seasonal variation of the thermal length during one year for one residential building.

2.8.1 Proposed: Poseidon, Gothenburg, Sweden

This case contains the input from 101 of the 109 buildings analysed by (Jangsten et al., 2017) in the previous possibility. Estimated thermal lengths are presented in Figure 8 by design outdoor temperature and construction year. The corresponding supply and return temperatures were obtained directly from the author since they were not reproduced in the paper. The estimated indoor temperature was set to 22°C, which is the average indoor temperature recorded for Swedish multi-family buildings for many years.

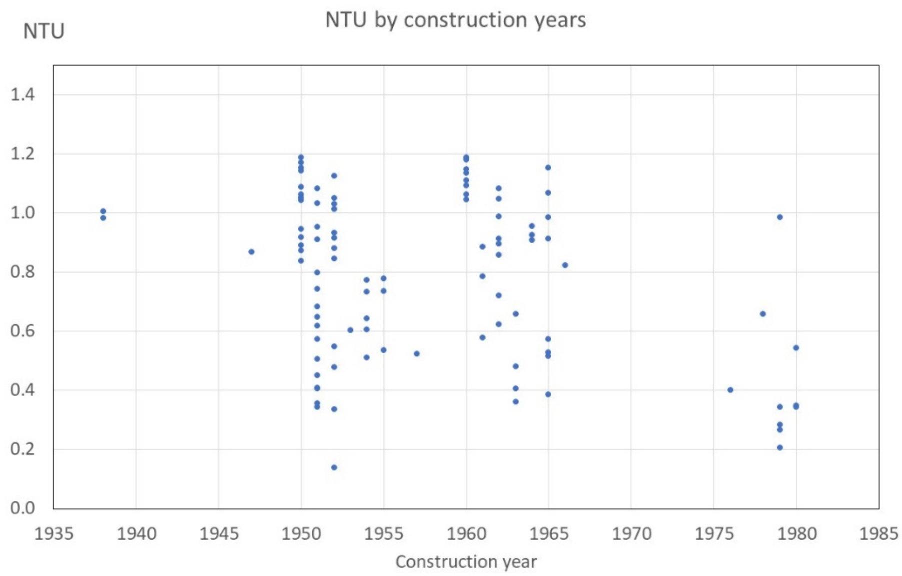

Figure 8. Thermal lengths (NTU) at design outdoor temperature (-16°C) for 101 multi-family buildings in Gothenburg belonging to the municipal housing company Poseidon.

This group of 101 buildings showed a six-fold variation from high values reaching NTUs of 1.2 to low values of 0.2. High NTU values indicate good conditions for using low radiator temperatures.

This high variation in effective thermal lengths does not correlate with the construction year. Hence, the variation has individual explanations and the actual reasons for short effective thermal lengths can only be identified by site inspections of the radiator systems. However, it is very unlikely that the performance of radiators varies by size by a factor of six since they have been designed according to the same standard applied during each construction year. Instead, it is likely that shortcuts or unintended high flows exist in radiator systems with short effective thermal lengths. Thus, a discrepancy can exist between the design and effective thermal lengths.

2.8.2 Proposed: Backa Röd, Gothenburg, Sweden

The second case also comes from the Poseidon company in Gothenburg but was not included in the Jangsten group of buildings. The building, called Backa Röd, was a Swedish example in the IEA-EBC Annex 56 project concerning shining examples of energy renovations of buildings (Morck et al., 2015). After the energy renovation, the total energy use was reduced by 65%. Detailed information about this energy renovation project is available on pages 85–90 in (Brito et al., 2014).

The daily averages of the supply and return temperatures during 2018, together with the corresponding outdoor temperatures, were obtained from the building surveillance system at the Poseidon company. The estimated indoor temperature was set to 22°C.

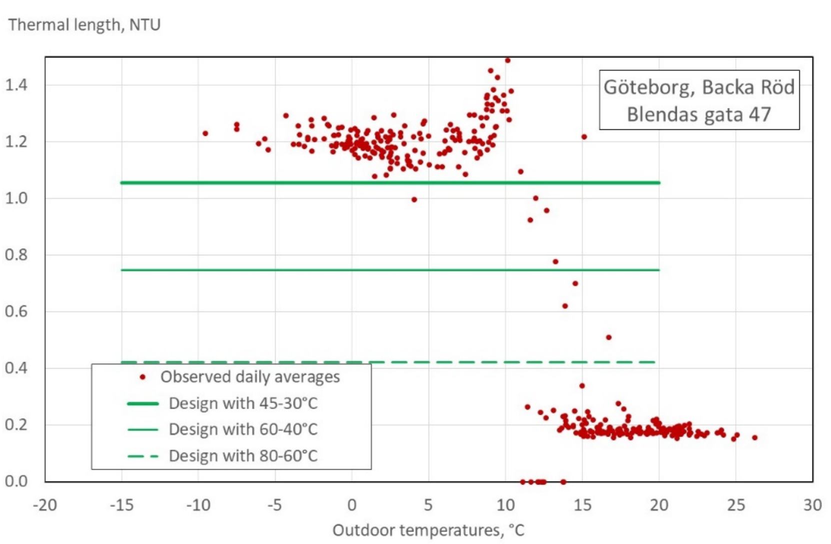

Figure 9. Seasonal variation of daily averages of the thermal length NTU during one year for one multi-family building in Gothenburg, Sweden. The green horizontal lines indicate the expected design NTUs for three different design temperature cases.

The seasonal variation of daily averages of the thermal length is presented in Figure 9, showing stable wintertime values of 1.2. . Hence, this building has a proper radiator system suitable for low temperatures for space heating.

Link:
https://www.iea-ebc.org/projects/project?AnnexID=56

2.8.3 Proposed: Tjärna Ängar, Borlänge, Sweden

The third case follows the same approach as the second case, yet the objective is different. This building is located in Borlänge and is owned and operated by

Tunabyggen, the local municipal housing company. The temperatures required for the analysis were obtained directly from Dalarna University since they were not published in any report. The origin of the case was a research project concerning cautious energy renovations of multi-family buildings performed together with Tunabyggen.

The outcome of the analysis is presented in Figure 10. The wintertime NTU values vary between 0.5 and 0.6 However, this building is operated with rather low temperatures. When approaching an outdoor temperature of -15°C, the supply temperature is about 50°C with a return temperature of 38°C. The narrow difference of 12°C indicates that a high radiator flow is applied, giving a reduced effective thermal length for this system. Only an on-site inspection can explain the cause of the high radiator flow, which negatively affects the thermal length of this radiator system.

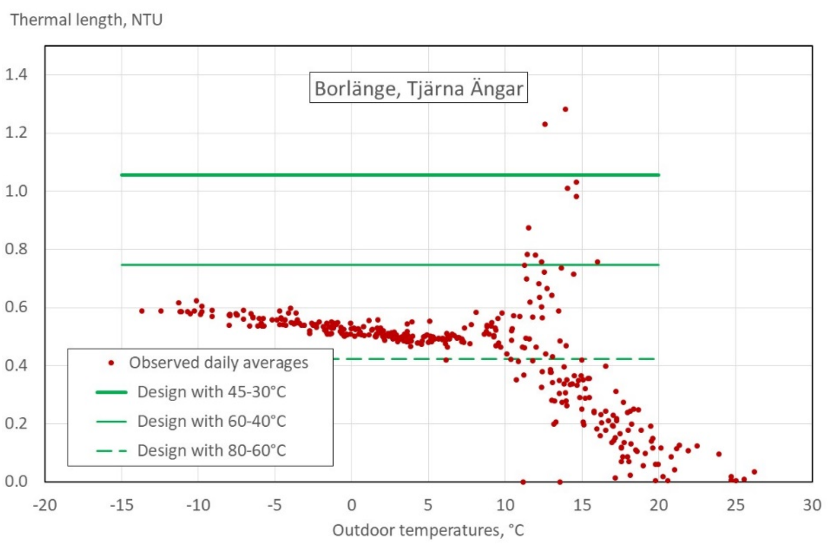

Figure 10. Seasonal variation of daily averages of the thermal length NTU over 12 months from 27 August 27, 2018 to 26 August 2019, for one multi-family building in Borlänge, Sweden. The green horizontal lines indicate the expected design NTUs for three different design temperature cases.

Link:
https://www.du.se/en/research/research-projects2/?code=HDA2015-00017

2.9 SUMMARY CONCERNING USING HEAT

This chapter covered two main aspects of using heat. One is how heat is used and how to track deviations; the other is heat use applications other than space heating and domestic hot water.

The decarbonisation options associated with using heat are reducing fossil fuel usage for connected customers, achieving a more efficient usage of delivered heat, and using lower temperatures in heat distribution networks.

As system temperatures and heat demands will decrease in the future, it will be important for district heating operators to identify both unfavourable heat use and unconventional heat demands to stay competitive.

3 Connecting customers

This chapter presents six possibilities concerning the connection of customers, considering both the configuration of substations and fault detection. These approaches offer increased efficiency and reliability, reduced heat demand, and lower temperatures, thereby increasing the possibility of using unconventional heat sources with low or no carbon dioxide emissions.

As the natural connecting point, the substation is the focus of all the possibilities in this chapter. Possibility 3.1 deals with network layouts and proposes a unique substation for every flat. Possibility 3.2 deals with the use of an absorption heat pump to lower the return temperature. Possibility 3.3 highlights the importance of fault standardisation. The other possibilities (3.4, 3.5, 3.6) concern tracking and handling data from the substation.

An overview of the locations of the cases concerning connecting customers is presented in Figure 10.

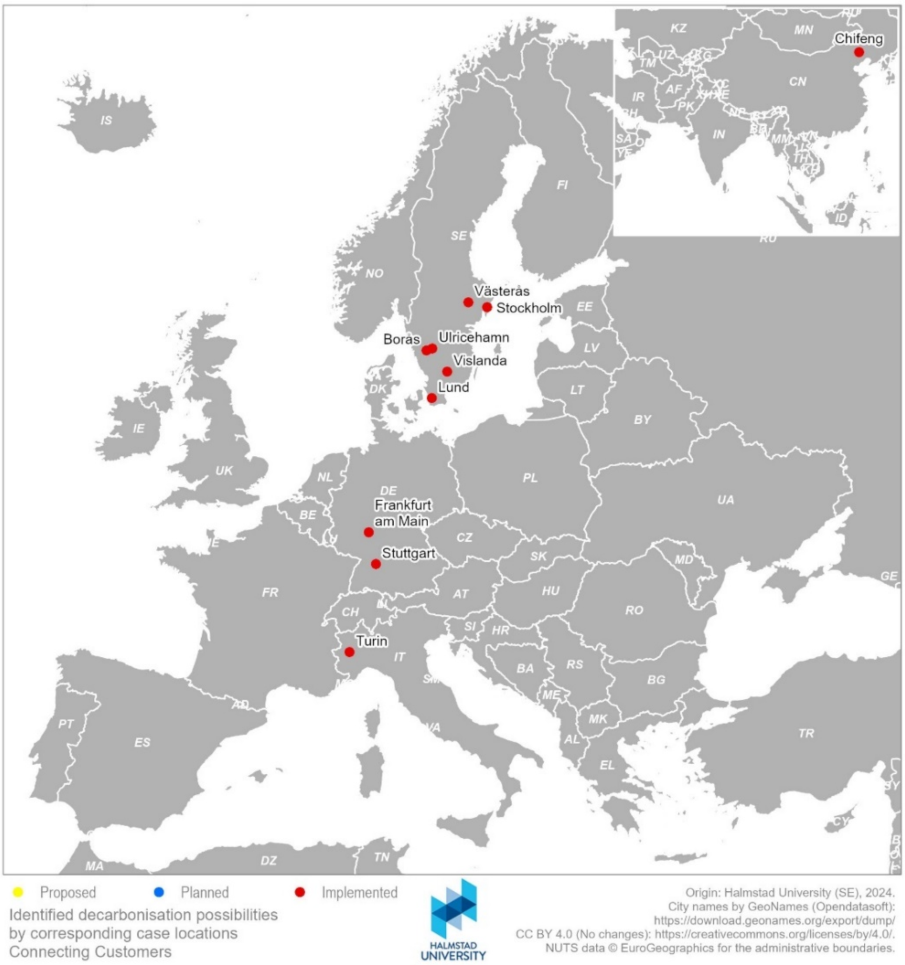

Figure 11. Map showing the locations of cases in the database concerning connecting customers.

3.1 FLAT SUBSTATIONS

This possibility regards installing substations in each flat of new multi-dwelling buildings. Internationally, there are three different customer interfaces: group substations delivering heat to a group of buildings, building substations delivering heat to one building, and flat substations delivering heat to one flat.

One substation serving each building is the most common customer interface in Europe, while group stations are common in Russia and China. Flat substations are becoming more frequent in Europe, where individual gas boilers in multi-family buildings should be substituted with district heating in both existing and new buildings.

Individual substations in new multi-dwelling buildings have several advantages. Tenants can choose individual temperatures; it is possible to have an individual billing; and the risk of legionella is eliminated or at least minimised because of the very small volumes of heated domestic hot water. At the system level, it also decreases the temperature demand for the heat supply, thereby enabling low-grade heat to be further utilised in district heating systems.

3.1.1 2020: Grand Tower, Frankfurt, Germany

Grand Tower in Frankfurt is a new multi-dwelling building with more than 400 flats. The building was completed in 2020. Each flat has an individual substation providing space heating, domestic hot water, and cold water, and the tenants can individually set the indoor temperature. The heat is supplied by district heating. The installed heat power is 2.5 MW; the cooling is supplied by two cooling machines in the building with an installed cooling power of 600 kW each. Each flat is supplied by three pipes (district heating supply, return, and fresh water) instead of the more common five pipes: heating circuit supply, return, cold fresh water, domestic hot water, and hot water circulation.

Link:
https://viomtankervatten.se/nyheter/grand-frankfurt-tower-varldens-mest-moderna-varmvattenlosning/

3.1.2 2020: Xplorion, Lund, Sweden

Xplorion in Lund is a new passive house solution in a low-energy housing block. It is part of a full-scale test in an EU project, COOL DH, which aims to demonstrate and evaluate technical solutions for utilising very low-grade surplus heat for low-temperature district heating.

Xplorion is designed for a primary supply temperature below 50°C and is boosted by a heat pump on the secondary side to deliver a supply temperature of 60°C to the flats. The return temperatures from the flats are between 25 and 30°C. Each flat has its own substation, and the tenants can control the indoor temperature in each flat.

Reference: (Moallemi et al., 2023a)

Link:

http://www.cooldh.eu/

3.2 LOCAL REDUCTION OF THE RETURN TEMPERATURE

An absorption heat pump (AHP) can be integrated into the substation as a means of using lower temperature heat sources as well as increasing system efficiency and thus the network capacity. There are two cases describing this technology, one in China and one in Germany.

3.2.1 2008: Chifeng, China

In China, there has been a growing interest in co-generation based on absorption heat exchangers (co-ah cycle), with implemented projects showing promising results, to lower the return temperature and increase the transport capacity, thus enabling the use of lower-temperature heat sources. Compared to conventional district heating, co-ah has shown significantly higher heating capacity, heat transmission capacity, and exergetic efficiency, and lower monetary cost (Sun et al., 2012).

After a demonstration project was tested in Chifeng city in 2008 (Li et al., 2011), (Li et al., 2011), the first large-scale industrial application was built in Datong City. The absorption heat pump uses the large temperature difference between the primary and second networks as the driver, and the return temperature can be decreased from 70°C to 20°C. The results showed an increased delivery capacity of the heat network by 40% and an increased heating capacity by 50% (Li et al., 2015).

3.2.2 2018: University of Stuttgart, Stuttgart, Germany

At the University of Stuttgart, an ammonia-water absorption heat pump has been proposed to reduce the return temperature in the district heating network (Mirl et al., 2018). The flow in the district heating network is used to power the heat pump and the district heating return flow is cooled in the heat pump evaporator, enabling a network return temperature below the return temperature from customers. By doing so, the capacity of the district heating system can be increased while the mass flow is reduced as the lower return temperature increases the overall system efficiency.

3.3 FAULT STANDARDISATION IN SUBSTATIONS

Decreasing faults in substations is crucial for both building better, more reliable DH systems and lowering the system temperatures. Fault standardisation is important for knowledge sharing between separate systems.

In a PhD thesis from 2021 at Lund University (Månsson, 2021), Sara Månsson dealt with fault handling in customer substations to identify and understand the challenges associated with handling customer data in the utilities' fault handling process. Some faults are more common than others: leakages and faults in the customers' internal heating system (Månsson et al., 2019). The utility–customer relationship was found to be crucial to identifying and correcting faults to obtain the desired low return temperatures. Key factors included physical access to installations, service agreements, and customer incentives for being active in detecting and correcting faults. The use of substation data to identify faulting substations is also deemed important, and in an approach built on machine learning is proposed. Furthermore, a taxonomy for fault labels is developed by (Månsson et al., 2021).

3.3.1 2018: K2, Smart Energi, Stockholm, Sweden

K2 is an open-source software for automated fault detection in district heating systems on the user side, in substations, and in the users' secondary heat systems. The software was developed and is maintained by Smart Energi, *https://smartenergi.org/*, which is a cooperation of 11 district heating operators in Sweden. K2 uses data analytic methods to detect deviations from a desired operation. It offers the opportunity to identify faults as they appear and increases the knowledge of the customer's heat demand pattern. The software is web-based and open-source for members of Smart Energi. The installation can be in the cloud or on-premise, and there are APIs available for data imports.

3.3.2 2019: Borås Energi & Miljö, Borås, Sweden

Borås Energi & Miljö has used K2 for a few years to identify faults in customer installations, including heat meters. Compared to earlier years, customer analyses are now conducted daily instead of monthly. Discovered faults are labelled according to the taxonomy described in the introduction of this chapter.

Once enough data has been collected, the intention is to use K2 to develop automated fault detection to be proactive for customers. Today, about 30% of the fault detection is proactive and the remaining 70% comes through customers contacting Borås Energi & Miljö because they have a problem. Figure 12 shows the flow from reported faults to the identification of broken components.

An interesting side effect is that fewer faults occur during the billing preparation at the end of the month because faults that were previously discovered during the billing process are now discovered sooner.

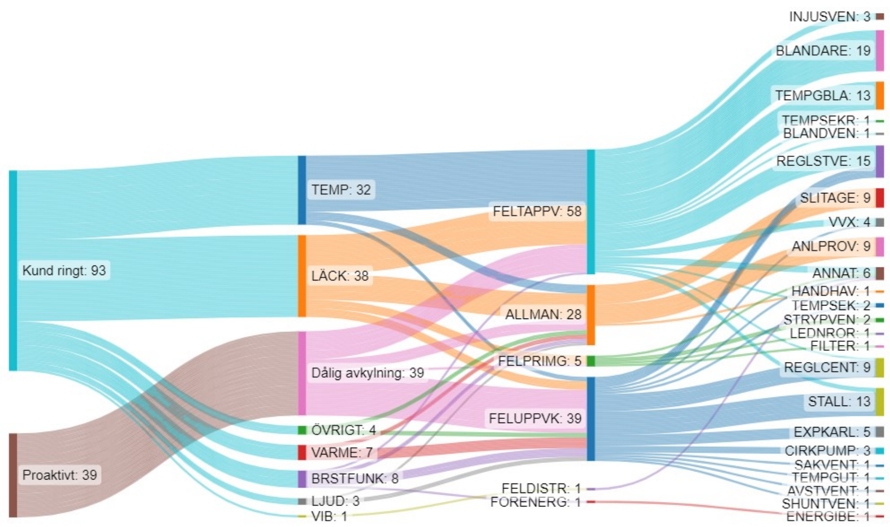

Figure 12. Structure and corresponding frequencies of fault labelling at Borås Energi & Miljö. (Published with permission from Borås Energi & Miljö)

Reference: Personal communication with Borås Energi & Miljö.

3.4 SUPERVISION OF SUBSTATIONS

This possibility involves using inter-connected substations for automatic supervision and fault detection. It aims to use high-resolution, real-time data to optimise system operations. Besides the obvious benefits of fault detection, other advantages include the improved control of supply and return temperatures, enabling lower temperatures and thus reduced heat loads.

3.4.1 2020: The iHAST project, Frankfurt, Germany

The implemented project Intelligente Hausanschlussstationen (intelligent house connection stations) or iHAST, which was led by the German combined heat and power organisation AGFW, focused on the digitalisation of district heating operations (EHP-Redaktion, 2020, Springer et al., 2020). Intelligent house connection stations and self-learning network operation systems were developed and tested on several participating utilities running district heating networks. When iHAST was implemented to improve the controllability of supply and return temperatures, the temperatures could be reduced, resulting in heat load reductions between 6–8%. Furthermore, the district heating networks that used the optional load shift of the domestic hot water demand made additional savings in fuel usage (0.6%) and carbon dioxide emissions (0.5%).

Link:
https://www.agfw.de/ihast

3.4.2 2021:Substation gateways, Stockholm Exergi, Stockholm, Sweden

To utilise the possibilities associated with digitalisation, the public utility company Stockholm Exergi began a project in 2019–2021 where gateways were installed in 7,300 substations in both their district heating and district cooling grids The gateways, which replaced the old system based on meter readings, can both gather data and control the substations remotely. This technology can, for example, be used in extreme situations where a faulting heat source limits the heat supply. Based on the real-time data gathered from the substation's gateways, the heat supply can be re-directed to where the heat shortage is greatest, thus keeping the temperature drop to a minimum. The gateways can also be used for fault detection and heat control by the customer. All 16 000 substations are planned to have gateways installed by the end of 2025.

Link:
https://www.stockholmexergi.se/nyheter/vad-ar-det-stockholm-exergi-installerar-i-fjarrvarmecentralerna/

3.5 TRACKING DEVIATIONS IN SUBSTATIONS

To detect faults and optimise both existing and future DH networks, it is important to track and log high-resolution measurements from substations in DH systems. Advances in data handling, including machine learning, allow for finding faults more efficiently and achieving lower return temperatures.

Link:
https://www.energi.se/artiklar/2024/januari-2024/det-finns-mycket-pengar-att-spara-genom-effektiva-fjarrvarmecentraler/

3.5.1 2020: Borås Energi & Miljö, Borås, Sweden

In the implemented pilot project Data Analytics for Fault Detection in District Heating (DAD), Borås University and its industrial partners developed new methods and algorithms involving machine learning for predictive data analytics. This included the automated detection of abnormal behaviour in a customer substation through the development of the Univariate Time Series Anomaly Labelling (UTAL) algorithm. The DAD project also included the detection of sub-optimally tuned substations. A high-dimensional large-scale anomaly detection algorithm was developed to study a large number of customer facilities for suboptimal behaviour over long periods (Mbiydzenyuy, 2020). Furthermore, work on the classification of detected abnormal behaviour was part of the DAD project. The Anomaly Pattern Detection (APD) algorithm was developed to replicate labelling knowledge on larger dataset (Mbiydzenyuy and Sundell, 2022).

Link:
https://www.hb.se/en/research/research-portal/projects/data-analytics-for-fault-detection-in-district-heating-dad/

3.5.2 2022: Data Science BRAVA, Stockholm, Sweden

The implemented project Data Science BRAVA was a collaborative effort between academia, data scientists, and district heating companies to improve precision in identifying anomalies and patterns in heat distribution (Wästberg et al., 2022). One project aim was to find this data and make it available, for example by developing a framework for data sharing. Another goal was to develop and improve algorithms and analytical models and apply them in reality, such as the analytical model ARNOLD for enhanced fault detection.

Improving collective competence in the district heating field was also a key goal of the project. This included finding models for collaborations between energy distribution operators, universities, AI, and data experts.

Link:
http://smartenergi.org/datasciencebrava/

3.5.3 2022: Ulricehamns Energi, Ulricehamn, Sweden

In an implemented project, the return temperature in the public utility-owned district heating network in Ulricehamn was lowered using real-time measurements and automated fault detection. Ulricehamn Energi has operated since 2001; today, 65% of the heat is recycled excess heat and 30% comes from wood pellets (Borglund, 2021). This relatively new DH system has about 330 customers in a 32 km network using 50 GWh. The system is distinguished by its altitude difference of 144 m as well as for having relatively few but large customers. To lower the return temperature, Ulricehamn Energi has logged hourly data values for all customers since 2005 and uses a real-time quality index to find faults in substations. The company's strategy for lowering the return temperature in the DH network comprises the following four measures:

1. Automated detection of errors, preferably with metering and sensors.
2. When deviations occur, there must be a prompt visit for the inventory of the error.
3. Documentation of all errors and their causes, both technical and behavioural caused by the customer.
4. Reporting back to the customer; learning from the errors to improve the company's error detection.

The strategy has resulted in a lower aggregated return temperature: the annual average has been reduced from 45°C to 39°C.

Link:
https://www.energi.se/artiklar/2022/januari-2022/sa-har-ulricehamns-energi-kapat-fjarrvarmekostnaderna/

3.6 TRACKING THERMAL LENGTHS IN HEAT EXCHANGERS

To lower the temperatures of a DH system, a higher NTU (Number of Thermal Units) is needed. This implies that NTU values should be tracked by using high-resolution measurements to identify fouling in the heat exchangers used in substations. The following case is an example of software developed for completing this task in large networks without needing new and expensive equipment.

3.6.1 2020: IREN, Turin, Italy

A tool for automatic fault detection in large heat exchanger networks has been presented in a scientific paper (Guelpa and Verda, 2020). The tool is not dependent on information such as the heat exchanger's type, dimension, or geometry. This makes it useful for large networks built over time, where little information is available on all the network's components. The tool's input data only consists of the mass flow rate and temperature, which are typically gathered for billing purposes. The software was developed to provide a graphical output (see Figure 13), which can be used for planning and managing network cleaning schedules.

The software was tested on various heat distribution systems in Turin, which are operated by the local utility IREN. The estimated benefits included an average energy input decrease of about 1.6% due to the more efficient cleaning schedule.

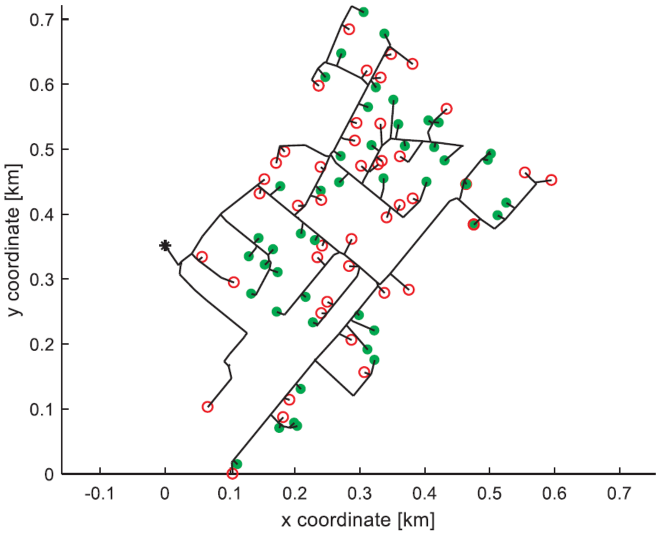

Figure 13: Graphical output example from the proposed software on one of the tested Turin DH distribution systems. A green marker means that the heat exchanger is clean; a red marker indicates a need for cleaning or other malfunctioning. Image used with permission from Elisa Guelpa (Guelpa and Verda, 2020).

3.7 SUMMARY CONCERNING CONNECTING CUSTOMERS

This chapter described possibilities regarding the connection of customers to district heating networks with a focus on the substation, which is the natural connection point. Collecting and handling data from the substation to improve the district heating network, whether in real time or not, is the focus of several possibilities, particularly to lower heat usage and return temperatures and improve the overall network performance. Other possibilities include fault standardisation and using individual flat substations and absorption heat pumps to lower return temperatures.

The focus on improving the customer side has historically been low since this typically entailed a lot of manual work and high costs. Automatic data collection from building management systems and meter reading systems has greatly reduced the costs associated with the optimisation of the customer interface and customers' internal systems.

4 Moving heat

Moving heat in heat distribution networks is associated with 12 different possibilities that directly or indirectly support decarbonisation, either by using lower heat distribution temperatures, lowering construction costs, or lowering operating and maintenance costs.

Achieving lower distribution temperatures is an important step to lower the heat supply costs for most decarbonised heat supply options. This important issue has been explored in an extensive implementation guidebook concerning low-temperature district heating (Averfalk et al., 2021).

The first six possibilities consider various implemented network configurations for applying low-temperature district heating. These six configuration groups consider both warm and cold networks, where a cold network denotes a network with a supply temperature below 50°C. A more comprehensive overview of these six possibilities is available in (Werner, 2022).

The seventh possibility concerns lower construction costs with plastic pipes when using lower heat distribution temperatures. The eighth possibility explores decentralised heat supply from low-cost heat sources. The ninth and tenth possibilities are two examples of using lower heat distribution temperatures, while the two final possibilities focus on lowering the risk of internal corrosion in the distribution pipes through automated monitoring. The latter is important in low-temperature networks since water can contain higher concentrations of oxygen when it is colder according to Henry's law.

An overview of the locations of the identified cases concerning moving heat in distribution networks is presented in Figure 14.

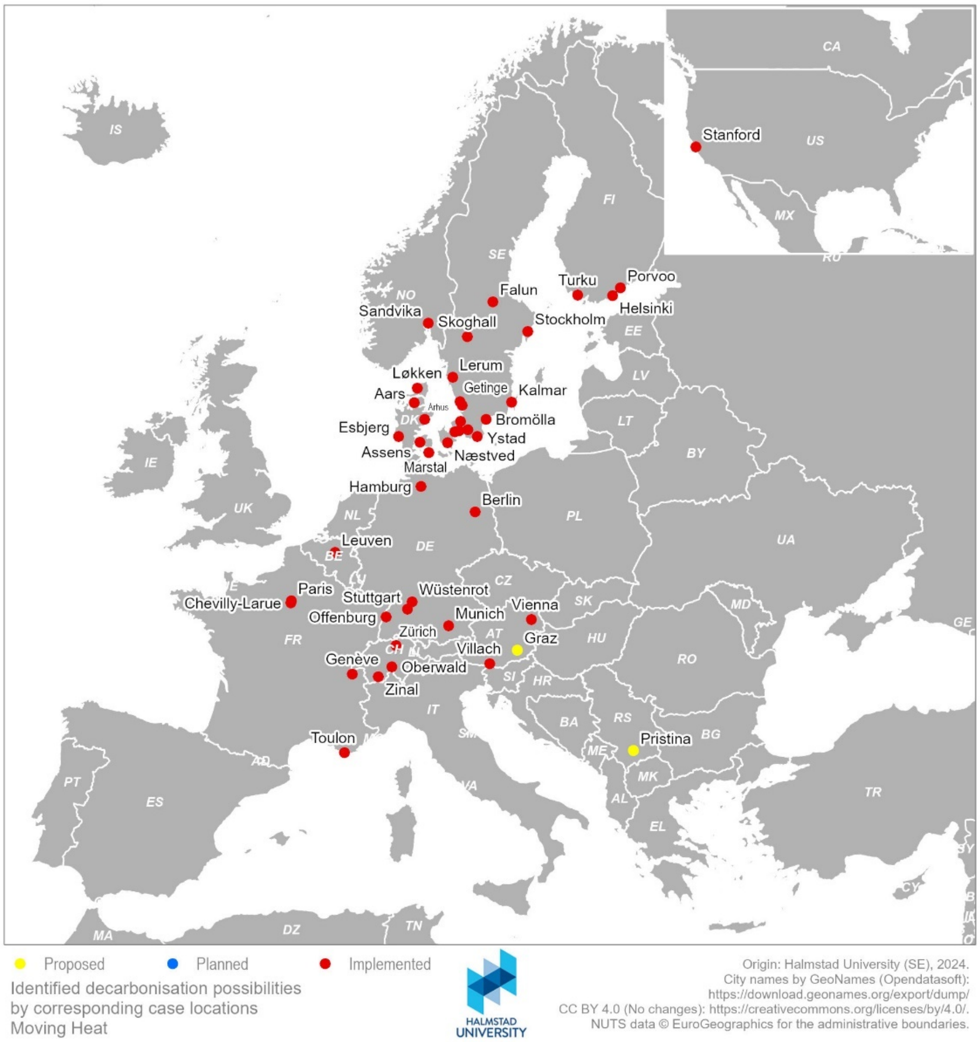

Figure 14. Map showing the locations of cases in the database concerning moving heat.

4.1 CLASSIC CONFIGURATIONS

This low-temperature network configuration has been described by (Werner, 2022) as similar to the conventional systems found in Scandinavia and elsewhere but with much lower system temperatures. The supply temperature is pushed below 60–65°C but is still higher than the minimum necessary for domestic hot water and the prevention of legionella growth. The return temperature is aimed to be lowered to 30–35°C by fixing issues in existing networks, substations, and consumers' heating systems.

(Werner, 2022) identified two variants of this network type: the supply-to-supply connection and the return-to-return connection. In the first type, consumers with high return temperatures are connected to the supply pipe to deliver their return flows directly to the supply flow, preventing temperature pollution of the return flow.

In the second network type, a consumer or subsystem with low-temperature requirements is mostly supplied by the return flow of the main system. The main benefits of this type of connection are the reduction of heat losses and increased generation efficiency from the lower return temperature or increased network capacity following minimum investments (Volkova et al., 2022). However, the higher impact in terms of return temperature reduction occurs on the outskirts of the network, where there may be capacity limitations (Werner, 2022). Conversely, locations closer to the production units can access more heat but may only achieve smaller decreases in the return temperature (Volkova et al., 2022).

References: (Moser et al., 2022, International Energy Agency (IEA), 2022)

4.1.1 2010: Lystrup, Denmark

The Danish project 'Full-scale demonstration of low temperature district heating in existing buildings' implemented a low-temperature subnetwork in a new development area of 40 houses built in 2009–2010.

All the houses were built with a combination of radiators and underfloor heating supplied with direct connections. Half of the substations were equipped with storage tanks, while the other half was supplied with plate heat exchangers for domestic hot water heating.

During the two-year measurement period (2011–2012), the supply temperature averaged 52–53°C and the return temperature reached 33°C, slightly higher than the 30°C goal.

The project showed the crucial importance of achieving adequate functioning of every substation since just a few consumers can have a disproportionate effect on the system's overall efficiency.

Reference: (Kaarup Olsen et al., 2014)

4.1.2 2019: Brunnshög, Lund, Sweden

As part of the COOL DH project, Lund's district heating company, Kraftringen, has developed a low-temperature district heating network in the Brunnshög area. Low-temperature heat at 60–65°C will be delivered by the new research facility MAX IV, which will also supply high-temperature heat at 70–80°C to the conventional network. The main advantage of the low-temperature network will be the higher efficiency in the heat recovery system from the particle accelerator compared to the efficiency achieved in the same plant for supplying the conventional system.

Furthermore, the new network has made extensive use of the new plastic PE-RT pipes developed by Kingspan-Logstor for the pipes with smaller diameters, while the trunk of the network uses conventional steel pipes. According to the manufacturer, the main benefits of the new pipes are associated with their installation further described in case 4.7.1.

Reference: (Moallemi et al., 2023a)

Link:
https://smartcitysweden.com/best-practice/407/max-iv-combines-high-tech-laboratory-with-high-tech-sustainability/

4.1.3 1995: Biond, Helsingborg, Sweden (supply-to-supply)

Biond is a biogas producer with two plants. One plant is in Helsingborg and produces 70–80 GWh of biogas annually. The feedstock for biogas production is organic waste from industries and households and manure from the agriculture sector. The biogas production process is mesophile, meaning the reactor temperature is 37°C. However, before the feedstock is pumped into the biogas reactor, it must be heated to 70°C for one hour for sanitation. The sanitation is performed with district heating, then the 70°C return goes back into the supply line of the district heating network. The heat supply is about 6 GWh annually.

This case is on the same site as case 2.3.1.

Links:
https://www.ox2.com/sv/pressrum/pressmeddelanden/2018/ox2-bygger-ny-forbehandlingsanlaggning-for-biogas-i-helsingborg/
https://www.biond.se/anlaggningar/

4.1.4 2009: Hyttkammaren, Falun, Sweden (return-to-return)

The Hyttkammaren tower block and Falun's theatre have been supplied by a combination of supply and return flows since their respective constructions in 2009 and 2020.

In the residential complex, the return flow of 40°C is used for underfloor heating, which only requires a temperature up to 27°, while the supply flow is dedicated to domestic hot water preparation, some radiators, and air heating. In this building, the return flow accounts for 42% of the heat used, while the supply flow delivers the remaining 58%.

The theatre follows a similar scheme; however, in this case, the return flow is also used for the air handling unit. This leads to higher use of the return flow (57%) compared to the previous case.

The main driver for Falun's company has been to improve the efficiency of the flue gas condensation system by reducing the return temperature. The company translates this benefit to consumers by means of a reduced variable rate for the return flow and the removal of the fixed component.

Reference: (Kretz, 2021)

4.2 MODIFIED CLASSIC CONFIGURATIONS

The purpose of a modified classic configuration is to overcome current constraints in the classic configuration to achieve lower network temperatures. This is achieved by implementing modifications to reduce the distribution temperatures by 10°C on average compared to what is possible in the traditional classic configuration. This configuration aims to reach a supply temperature at customer substations of 50°C and a return temperature of almost 20°C.

The main modification to the traditional configuration has been the introduction of a small third pipe. This pipe takes care of the small circulation flow, providing a stable supply temperature for the preparation of domestic hot water when no space heating occurs. Another modification is to use heat exchangers with longer thermal lengths in the substations to facilitate lower supply temperatures in the network.

These modification ideas were made available through (Averfalk and Werner, 2017) and later through (Averfalk and Werner, 2018). Another study concerning design conditions for the third pipe in this configuration was published by Averfalk et al. (2019). The economic drivers for the configuration have been explored by (Averfalk and Werner, 2020).

4.2.1 2022: Ranagård, Halmstad, Sweden

The first network to use this new configuration was implemented in part of the newly built Ranagård area in Halmstad. The construction phase is reported in detail in (Norrström et al., 2022). The planned annual heat delivery in this sub-network is about 2 GWh with an average specific heat demand of 76 kWh per square metre of building space. The area has both single- and multi-family buildings, resulting in a low heat density of only 30 kWh per square metre of land area.

The first heat delivery occurred in November 2022. The trench length of each of the three installed pipes is 2.9 km, corresponding to a total pipe length of 8.7 km.

The intention is to perform an evaluation study to verify and compare the actual operating conditions with the results from the previous computer simulations. The network temperatures will be measured for a year after all the buildings are connected in 2024–2025.

4.3 MULTI-LEVEL CONFIGURATIONS

This network configuration is characterised by the existence of at least two supply pipes delivering heat at different temperatures. Consumers are connected to the network using the supply and return pipes that best fit their temperature requirements.

The main advantages of this configuration are that consumers receive heat at the temperature best suited for their needs and the possibility of reaching lower return temperatures. The main drawbacks are the need for a series of parallel pipes and the challenge of balancing the demands of all consumers.

4.3.1 1985: SEMHACH, Chevilly-Larue, France

The district heating system of Chevilly-Larue, L'Haÿ-les-Roses, and Villejuif (outskirts of Paris), operated by SEMHACH, has been developed based on a network with up to four supply pipes with different temperature levels. These temperature levels are classified as high temperature (>60°C), medium temperature (45–60°C), low temperature (35–45°C), and very low temperature (<35°C). As of 2023, the network has 25 km of trenches and 80 km of pipes with an average of 3.2 pipes in parallel.

The aim of the different temperature levels is to take advantage of the geothermal resource (73°C) as much as possible by delivering only the required temperature at each building. This allows for reducing the return temperature and maximising the temperature difference in the network and, hence, the amount of geothermal energy available.

References: (Faessler and Lachal, 2017, Faessler, 2015, Faessler, 2016, SEMHACH, 2023)

4.3.2 2018: NeckarPark, Stuttgart, Germany

The brownfield development of NeckarPark in Stuttgart will be supplied with a four-pipe district heating network. The low-temperature network (43°C supply and 28°C return) will provide space heating and preheated mains water. The high-temperature grid (75°C supply and 50°C return) will be used to further warm the mains water and for domestic hot water preparation at an adequate temperature.

The main driver for this two-temperature level system was increasing the efficiency of heat production from a heat pump fed with sewage water. This unit will be supplemented by a co-generation unit and a gas boiler to meet peak loads.

Reference: (Erhorn et al., 2018)

4.3.3 2019: iGRID, Grundfos, Bjerringbro, Denmark

The Danish company Grundfos has developed the iGRID solution for creating tailored pressure and low-temperature zones in a district heating network (Grundfos, 2023c).

Grundfos' solution comprises four elements. The first is a prefabricated mixing loop which may be delivered in a cabinet, pit, or skid. This mixing loop blends the return and supply flows to reach the desired temperature. It can be configured in three modes: the free flow solution, which raises the pressure in the area; the shunt solution, which simply adds return flow; and the pressure reduction solution, which lowers the pressure in the supply flow. The second element is a temperature optimiser, that is, specialised software that uses real-time grid measurements to determine the lowest possible supply temperature. The third component is a pit measure point equipped with a thermal electric generator so that no connection to the power grid is needed. The fourth element, a bypass cabinet, ensures that a minimum temperature is available for critical consumers.

Grundfos has implemented this solution in two municipalities on the outskirts of Copenhagen: Gentofte (Grundfos, 2019, Grundfos, 2023a) and Albertslund (Grundfos, 2022, Grundfos, 2023b). In both cases, the main driver for the implementation of this product was reducing heat losses, which are rather high due to the low linear heat densities. The drop in supply temperatures could bring about increases in the efficiency of heat production (Geyer et al., 2021, Averfalk and Werner, 2020).

4.4 ULTRA-LOW CONFIGURATIONS

The main feature of an ultra-low configuration is that only low-temperature heat is delivered from a cold distribution network to the heat pumps in local customer substations. A cold distribution network is also used in the configuration layout presented in Section 4.5, which delivers cooling in addition to low-temperature heat from the same network.

Since the heat is distributed by a narrow temperature difference between the supply and return pipes in a cold distribution network, the distribution flow becomes considerably higher than in warm distribution networks. This creates a higher power demand for pumping (Ruesch et al., 2015). Based on current cost levels, the profitability of this configuration has been questioned (Gudmundsson et al., 2022). However, cost levels can change in the future, especially for small heat pumps manufactured in large numbers.

Three implemented cases using the ultra-low configuration in Switzerland, Germany, and Belgium are presented.

4.4.1 1991: Furka Tunnel, Oberwald, Switzerland

The drain water from the Furka railway tunnel has a flow of 90 litres per second with a temperature of 16°C. This has been the heat source for a group of buildings in the Oberwald village in the Wallis canton since 1991. The total connected capacity demand is about 1 MW, while the available flow and temperature can supply 3 MW. The references below present other villages in Switzerland using tunnel waters for heating purposes, the oldest was commissioned in 1979.

References: (Rybach, 1995), (Rybach and Wilhelm, 1995) and (Rybach et al., 2003)

4.4.2 2011: Agrothermie, Wüstenrot, Germany

The Agrothermie project in Wüstenrot started in 2011 with a pilot project for 23 residential buildings having a total annual heat demand of 340 MWh. The supplied heat is extracted from ambient heat by a novel shallow horizontal geothermal collector, also called an agrothermal collector. The heat is transferred to the customer substations by a cold network with a temperature ranging between 2°C and 16°C during the year. The network consists of a two-pipe system with a DN250 diameter for distribution pipes, DN40 for service pipes, and a total trench length of 500 m. The decentralised customer heat pumps have thermal outputs between 6 and 20 kW depending on the building size. The heat pumps deliver temperatures of 30–40°C for underfloor space heating and 50–55°C for domestic hot water. The monthly average coefficient of performance (COP) of each heat pump varies between 3.6 and 4.5 during the year.

This project includes an option for future cooling deliveries to be transferred to a cold CHC configuration. The agrothermal collectors and the performed extension of the system are more closely described in Sub-section 7.5.1.

Reference: (Brennenstuhl et al., 2019)

4.4.3 2017: Janseniushof, Leuven, Belgium

This pilot project is related to a new master plan for urban renewal of the Leuven city centre. The Janseniushof project covers a 25,000 m^2 area that was previously used for the car park of a hospital campus. The project comprises 206 housing units built in four construction phases. The final two phases serve as the pilot for the aquifer thermal energy system (ATES) and low-temperature energy network.

The low-temperature heat distribution network with uninsulated pipes moves heat from three geothermal doublets and allows for the possibility of recharging the doublets with heat from the river Dijle, which runs through the project area. The operating temperatures are 14°C for the supply and 8°C for the return. In multi-family houses, the heat is upgraded to 40°C with heat pumps for space heating and preheating domestic hot water. Local booster heat pumps provide additional heating to deliver domestic hot water at 55°C.

This project also offers the option of transferring cooling deliveries to a cold CHC configuration in the future. The gained experiences from this pilot project will be used in the renovation of the former hospital campus area of 6,800 m^2, called Hertogensite, which is located next to the Janseniushof area.

Reference: (Pattijn and Baumans, 2017)

4.5 COLD CHC CONFIGURATIONS

According to (Werner, 2022), Cold Combined Heating and Cooling networks are characterised by the delivery of both heating and cooling, making them similar to Warm Combined Heating and Cooling networks. However, in CHC configurations, the system temperatures are insufficient for the direct preparation of domestic hot water.

The main advantage of CHC is the exploitation of the simultaneous production of heating and cooling in the same network. Its main drawbacks lie in the decentralisation of heat and cooling production, which hinders the implementation of economies of scale in heat production and thermal storage and the use of increased flow rates due to the small temperature differences. Moreover, it can require some consumers to be equipped with pumping equipment.

Werner has also identified two variants of this configuration. In the first variant, temperatures are high enough for space heating, but a booster heat pump is required for domestic hot water and a chiller is needed for cooling. In the second variant, the cold pipe's temperature suffices to deliver cooling through a substation, but a heat pump is required to meet the entire heat demand.

4.5.1 2013: FGZ, Zürich, Switzerland

The housing cooperative Familienheim-Genossenschaft Zürich has developed a cold network of uninsulated pipes on the outskirts of Zürich starting in 2011. The network provides cooling to two data centres nearby, and the excess heat is either used or stored in a borehole thermal storage for the winter period. The water temperatures in the network vary over the year, ranging from 8°C to 28°C. The water is used to deliver heat to an array of decentralised heat pumps located in each building, which provide space heating and domestic hot water at the required temperatures. As of 2018, the total heat demand was 35 GWh for a total floor area of 185,000 m^2. The network has been designed for continuous expansion up to the year 2050.

Source: (Kolb, 2018)

4.5.2 2017: Saclay University, Paris, France

The Paris-Saclay network was developed to supply a new university campus located 20 km south of Paris. It consists of a cold network with a 30°C supply and 12°C fed by geothermal heat which, in turn, supplies heat to several decentralised district heating production plants. These decentralised plants deliver heat to a warm network (63°C supply, 45°C return) and a district cooling system (6°C supply, 12°C return) that supply various consumers. To be connected, buildings must be able to function with a supply temperature of 55°C.

Although most of the heat and cooling stems from the Albein reservoir, gas boilers have been installed in the central production plant to meet peak loads by raising the temperature from 30°C to 90°C.

References: (Paris Saclay, 2019, Galindo Fernández et al., 2021)

4.5.3 2018: EON Ectogrid, Medicon Village, Lund, Sweden

The energy company E.ON has developed a cold network in the city of Lund to supply both heating and cooling. Each building is equipped with a heat pump that balances the heating and cooling needs of the building. The remaining load is met by the network, which has temperatures around 25°C and 15°C. The network is connected to a passive unit and an active balancing unit. The passive unit, consisting of an accumulator tank, equalises the heating and cooling flows; if this is not enough, the active unit corrects the disequilibrium.

The Medicon Village Ectogrid connects 15 buildings with a district heating demand of 10 GWh and a district cooling demand of 4 GWh. The long-term goal of the network is to balance 11 GWh with only 3 GWh of supplied energy.

Reference: (E.ON, 2023)

Link:
https://www.energi.se/artiklar/ectogrid-later-byggnader-dela-pa-varme-och-kyla/

4.6 WARM CHC CONFIGURATIONS

Heat recovery from cooling can also be accomplished when a district cooling network and a district heating system are available at the same location. In this case, the heat obtained from the condensers in the cooling system is transferred centrally to the heating system. This is called warm CHC since a warm network is used to distribute the heat from a colder district cooling network.

4.6.1 1989: Sandvika, Norway

When Baerum Energiverk commissioned two large heat pumps in 1989, this became the first major installation of warm CHC in Europe. Together, the two heat pumps could provide 13 MW of heat and 9 MW of cooling. These capacities were later increased. When cooling is not required in the winter, additional heat is extracted from a tunnel for untreated sewage water. The heat supply side of this warm CHC case is further described in case 8.7.1.

Link:
https://celsiuscity.eu/energy-recovered-from-sewage-water-in-sandvika-norway/

4.6.2 1995: Stockholm, Sweden

Stockholm commissioned its first district cooling system in 1995. A major part of the initial cooling supply was provided by large heat pumps introduced in the 1980s. The large heat pumps are installed on two major sites, Värtan and Hammarby, which are interconnected through district cooling networks. The heat pumps have a total heating capacity of 660 MW with a possible cooling output of 466 MW (Levihn, 2017). Since the cooling demand from connected customers is lower than the supply capacity, some excess cooling is emitted to the ambient, presenting excellent conditions for extensions of the district cooling system.

During 2022, half of the cooling generated for district cooling came from the large heat pumps. The remaining cooling came from free cooling from seawater (22%)

and mechanical chillers without heat recovery used to meet peak loads (27%). When cooling is not required in the winter, additional heat is extracted from seawater and treated sewage water.

The heat supply side of this warm CHC case is further described in Sub-section 8.7.2.

4.6.3 2006: Helsinki, Finland

The large heat pumps on the Katri Vala site were commissioned in 2006. Initially, this site had a capacity of 90 MW heating and 60 MW cooling. By 2023, these capacities have been increased to 155 MW heating and 104 MW cooling in seven parallel units, making Katri Vala one of the largest CHC sites in the world.

In 2022, the Katri Vala heat pumps were responsible for 91% of all cooling supply into the district cooling network of Helsinki. The remaining cooling supply came from free cooling from the sea and some mechanical and absorption chillers.

The heat supply side of this warm CHC case is further described in Sub-section 8.7.3.

Links:
https://www.helen.fi/en/about-us/energy/energy-production/power-plants/katri-vala-heating-and-cooling-plant
https://www.helen.fi/en/news/2020/new-heat-pump
https://energia.fi/en/newsroom/publications/district_cooling_statistics.html#material-view

4.6.4 2015: Stanford University, Stanford, USA

In 2015, this case became the first major warm CHC installation in the USA. It was a cornerstone of the Stanford Energy System Innovations (SESI) project, enabling a major transformation from one central gas CHP plant to central heat pumps powered by solar energy. The existing district cooling network from the 1960s was then connected to a newly built water-based district heating system, which replaced the old steam-based district heating system. Later, decisions were made to extend the cooling capacity of the district cooling system.

The heat supply side of this warm CHC case is further described in Sub-section 8.7.4.

References: (Stanford University, 2014), (Stagner, 2016), (Stanford News, 2020).

4.7 PLASTIC PIPES

The manufacturer Kingspan Logstor has developed a new type of flexible plastic pipes, the PE-RT pipes, within the EU-supported Cool DH project. These new pipes present a series of novelties compared to older plastic pipes.

1. PE-RT stands for polythene at raised temperature resistance, meaning this type of polythene is capable of withstanding high-temperature water in

district heating networks. This type of plastic had not been previously used for district heating pipes.

2. PE-RT pipes offer the possibility of using fusion welded joints, which increase the installation speed.
3. PE-RT pipes include a 3dc detection system consisting of three conductors, each of 0.75 mm^2, which can monitor the entire pipe system.
4. PE-RT pipes are recyclable, unlike PEX pipes, whose curing process is irreversible (Singh et al., 2019).
5. PE-RT pipes are available in larger sizes than multilayer PEX, aluminium, and PE-HD pipes.
6. PE-RT pipes include an aluminium diffusion barrier which is effective against the diffusion of oxygen, water vapour, and hazardous substances from the insulation foam. This is an improvement compared to the polymeric diffusion barriers in older plastic pipes, which only reduce oxygen diffusion.

References: (Jorsal, 2022b, Jorsal, 2022a)

4.7.1 2019: Cool DH, Lund, Sweden

Lund's district heating operator, Kraftringen, has used the new PE-RT pipes in the newly built low-temperature district heating network in the neighbourhood of Brunnshög. In this area, a total trench length of 735 m (84%) uses PE-RT pipes, while the remaining 137 m of the network use conventional steel pipes.

The project benefitted from the following advantages:

- Fast installation and reduced number of joints in long sections thanks to the pipes' flexibility and form of delivery (coils up to 100 m long), leading to a lower installation cost[1] compared to steel pipes.
- The flexibility of the pipes makes it easier to avoid obstacles and enables the use of narrower trenches.
- No need for steel welders.
- Plastic pipes in LTDH networks do not need bends for heat expansion, making the network design more straightforward.

However, the project also revealed these drawbacks:

- PE-RT is quite stiff, especially in larger sizes, which can make it difficult to join PE-RT pipes to T-joints and other pieces.
- The installation benefits decrease as the number of joints increases.
- There are limits to the size and casing of these pipes, especially when using twin pipes.
- PE-RT pipes become difficult to handle in cold weather below 10°C, making their installation more weather-dependent compared to steel pipes.

- PE-RT pipes with an aluminium barrier are slightly more expensive than PEX pipes and have a similar cost to steel pipes.
- PE-RT pipes have higher heat losses than steel pipes due to their small casing size.

  This case is in the same site as case 4.1.2.

Reference: (Moallemi et al., 2023a)

4.7.2 2019: Cool DH, Høje Taastrup, Denmark

PE-RT pipes have also been used in the new low-temperature network of Østerby in the Danish municipality of Høje Taastrup. While steel pipes were used for the main pipelines, PE-RT was used for most pipes in the network (93% of 3,119 m). This project had similar benefits and drawbacks to the Lund project.

Reference: (Moallemi et al., 2023b)

4.8 DECENTRALISED FEED-IN

Decentralised feed-in from solar heating is difficult to implement since the output must be a constant supply temperature whereas heat generation, the differential pressure, and the return temperature vary over the day. In (Lennermo et al., 2019), a system layout is described together with two applied control strategies: the temperature control strategy applied in Lerum and the flow control strategy applied in Ystad. Both locations are in Sweden.

4.8.1 2014: Lerum, Sweden

The solar plant in Lerum has 857 m² and has been in operation since 2014. The solar plant uses a temperature control strategy. The focus is on controlling the incoming temperature from the solar collector to achieve a suitable supply temperature from the current level of solar irradiation. From a piping point of view, the main difference compared to the flow control strategy described in the next sub-section is that the system has a short circuit on the primary side.

This case is on the same site as case 7.6.6

4.8.2 2017: Ystad, Sweden

The solar plant in Ystad has 534 m² and has been in operation since 2017. It uses a flow control strategy. The focus is on managing the requested supply temperature for the district heating network by controlling the flow through the solar collectors.

This case is on the same site as case 7.6.9.

4.9 TRACKING CIRCULATION FLOWS

Traditionally, district heating network models have been built based on geographic information regarding the network's topology and the pipe characteristics at the time of installation, complemented by measurements from production facilities and a few measuring points in the network. The deployment of smart heat meters offers the opportunity to use the massive amount of data on temperatures and flows to improve network models, making them much closer to the network's real performance.

The tool Heat Intelligence developed by Kamstrup combines a geographic information system (GIS) model of the network with data from heat meters in a model that shows the flows, temperatures, and pressures throughout the network. The model allows for detecting leakages, malfunctioning bypasses, and pipes with unexpectedly high losses.

Reference: (Kamstrup, 2023)

Link:
https://energiforskmedia.blob.core.windows.net/media/20704/rundgangars-ekonomiska-betydelse-for-fjarrvarmenaten-varmeforskrapport-525.pdf
https://www.kamstrup.com/se-se/news-and-events/news/goteborg-energi-och-kamstrup-samarbetar

4.9.1 2013: Assens, Denmark

The district heating system of Assens is monitored with the Heat Intelligence software from Kamstrup. As shown in Figure 15, the supply temperature was reduced over time, producing annual savings of 2.5–3 GWh according to the company.

Links:

https://www.kamstrup.com/se-se/kundreferenser/varme/case-assens-district-heating
https://fjernvarmen.danskfjernvarme.dk/p/magasinet-fjernvarmen/2019-09-27/a/optimering-rimer-pa-digitalisering/3045/356283/17425181

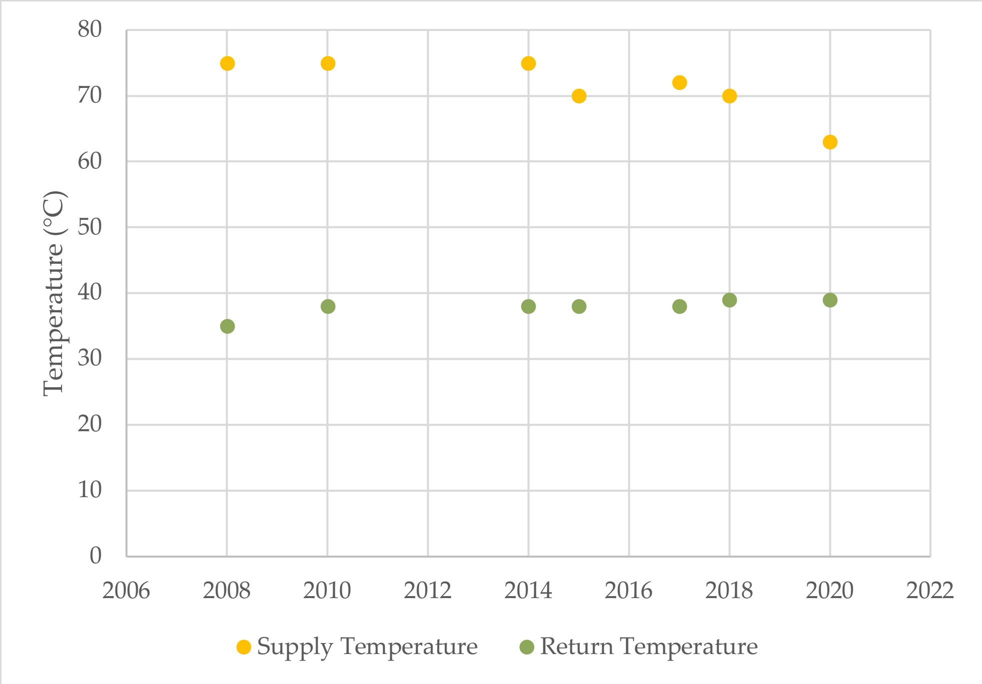

Figure 15. System temperatures in Assens. Sources: (Dansk Fjernvarme, 2008, Dansk Fjernvarme, 2010, Dansk Fjernvarme, 2012, Dansk Fjernvarme, 2014, Dansk Fjernvarme, 2015, Dansk Fjernvarme, 2017, Dansk Fjernvarme, 2018, Dansk Fjernvarme, 2019, Dansk Fjernvarme, 2020)

4.9.2 2018: Aars Fjernvarme, Aars, Denmark

The district heating system of Aars is monitored with the Heat Intelligence software from Kamstrup, which has enabled the reduction of the circulating flows from over 200 to 16. Even though the supply temperature decreased by 3°C, the return temperature decreased by 1.5°C in parts of the network.

Link:
https://www.kamstrup.com/se-se/kundreferenser/varme/aars-heat-intelligence

4.9.3 2020: Hammarö Energi, Skoghall, Sweden

Hammarö Energi has taken an initiative for tracking their circulation flows in their Skoghall heat distribution network. The outcome of their analysis is provided in Figure 16. The circulation flow was estimated as the annual differences between the recorded flows in the two heat supply units and all recorded flows in the connected substations. The reduction of the circulation flow during 2022 and 2023 refers to actions for flow reductions in service pipes without customers. The purpose of these circulation flows was to avoid ice formation in the pipes during cold winters.

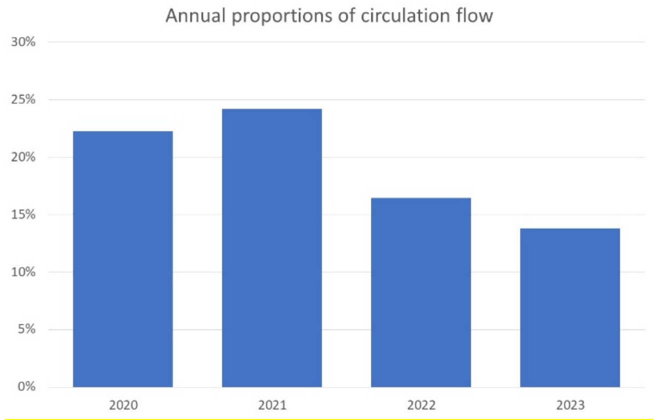

Figure 16. Annual proportions of the circulation flow in the Skoghall district heating system between 2020 and 2023. The proportions refer to the annual recorded flow volume in the heat supply units.

Reference: Personal correspondence with Hammarö Energi

4.10 CENTRAL REDUCTION OF THE RETURN TEMPERATURE

It has been well-known for decades that low return temperatures are beneficial. The most common way to achieve low return temperatures is to identify heat users with bad cooling and implement measures to improve the substation or the building. For low-temperature sources or central solar collectors and heat storage, it can be beneficial to have a central reduction of the return temperature by a heat pump. This has several advantages, including:

- Increased solar heat production
- Less storage required
- Lower storage temperatures
- Reduced heat loss from storage
- Using electricity in periods of high wind power generation and storing it as heat.

The three cases below all present solar district heating systems.

4.10.1 2012: Marstal Fjernvarme, Marstal, Denmark

SUNSTORE 4 is the project name for the construction of a solar collector with pit storage equipped with a heat pump in Marstal, Denmark. It has been in operation since 2012. The compressor-driven heat pump of 1.5 MW uses carbon dioxide as the refrigerant fluid to cool the storage to below 10°C in the winter period and produce hot water at 75–90°C. The heat supply system also includes a wood chip boiler for the winter period.

Reference: (Planenergi, 2013)

4.10.2 Planned: Pristina, Kosovo

A smaller version of the BIG Solar concept developed for Graz (see the next sub-section) is now planned for Pristina, Kosovo. The funding of the project was signed in 2022 and the estimated time of commissioning is the end of 2027.

The system will have a heat output capacity of 41 MW and provide an annual heat supply of 43 GWh. The system will include 410,000 m^3 of pit storage connected to a 20 MW absorption pump. Heat will be supplied to the absorption pump from the existing high-temperature district heating system. The system temperatures in the existing network are 120/60°C (supply/return), while the new district heating system will have temperatures of 80/60°C (supply/return).

This case is on the same site as case 7.6.16.

Links:
https://solarthermalworld.org/news/big-solar-in-kosovo-replaces-coal-based-electric-heating/
https://www.ebrd.com/news/2022/kosovo-becomes-first-western-balkans-economy-to-use-solar-energy-for-district-heating.html

4.10.3 Proposed: BIG Solar Graz, Graz, Austria

BIG Solar Graz was a proposed concept with a solar collector, pit storage, and an absorption heat pump to supply heat to Graz, Austria. With a collector area of 500,000 m^2, pit storage with a capacity of 1,000,000 m^3, and an absorption heat pump with a thermal capacity of 100 MW, the solar fraction could provide one-fifth of the heat supply of the Graz district heating system.

The absorption heat pump was intened to boost the temperature from the pit storage when needed. To further boost the temperature of the heat supply from the pit storage and the heat supply sent to the absorption heat pump, a separate high-temperature gas boiler is used. The temperature from the pit storage varied between 20 and 90°C; the supply temperature from the absorption heat pump to the network was planned to 85°C. This project was suggested to replace the Mellach coal-based CHP plant, which was closed in 2020.

This case is on the same site as case 7.6.17.

Reference: (Reiter et al., 2016)

4.11 AUTOMATED OXYGEN MEASUREMENT AND REMOVAL

Historically, degasification was not necessary to decrease corrosion in internal building heating systems because of the high system temperatures.

According to Henry's law, the ability to solve oxygen in water is higher at lower temperatures. This increases the corrosion risk in low-temperature heat distribution systems with steel pipes. In district heating systems, the standard solution to remove oxygen has been to measure its level at defined time intervals and then add chemicals to counteract corrosion. With lower temperatures in newly built district heating systems, combined with a drive to reduce the use of chemicals, the continuous measurement and removal of oxygen can decrease the risk of corrosion in low-temperature district heating systems.

4.11.1 2016: QTF, Kalmar, Sweden

For decades, the QTF company has provided oxygen removal equipment, mainly for internal building systems but also for several smaller low-temperature district heating systems in the Lessebo municipality, to decrease internal corrosion in the networks. Instead of adding oxygen-reducing chemicals, a vacuum is used for the degasification of the fluid. QTF's equipment can perform continuous measurement and degasification, bringing the oxygen content below 0.5 mg per litre.

Link:
https://qtf.se/home/

4.11.2 2020: Offenburg, Germany

Since 2020, the district heating network in Offenburg has benefitted from continuous degasification using equipment from Busch Vacuum Solutions. Due to environmental reasons, chemical degasification is not an option. Therefore, vacuum degasification technology is used instead. The degasification pump has become part of the continuous operation of the district heating system.

Reference: (Markanic, 2022)

Link:
https://www.buschvacuum.com/global/en/news-media/optimum-water-properties-in-the-district-heating-network-thanks-to-state-of-the-art-vacuum-technology.html

4.12 AUTOMATED CORROSION MEASUREMENT

Traditionally, corrosion measurements have been carried out on a discrete basis at strategic points of the district heating network. However, the drastic cost reduction of electronic equipment, and the advent of mobile data networks enable the continuous monitoring of corrosion parameters in an increasing number of points or network sections, and the retrieval and analysis of these data with minimal labour. Two examples of these technologies are the Rysicor, developed by the Belgian company Resus and the Smart Active Box, created and installed by Öresundskraft and Arne Jensen AB.

4.12.1 2022: Helsingborg, Sweden

Öresundskraft, the district heating operator of Helsingborg, has developed the Smart Active Box together with Arne Jensen AB. Installing a pair of these devices in two inspection chambers separated by a few hundred metres allows for the determination of the average thickness of the steel pipe, which indicates the strength of the steel. This process involves sending sound pulses along the pipe between the two devices.

A Smart Active Box (SAB), can also detect leakages and perform other measurements in the inspection chamber, such as the humidity, water, carbon dioxide, and oxygen levels, and district heating parameters such as water pressure and temperature. All measurement data is transferred over a mobile data network to be stored and presented in the SCADA system.

The device meets its electricity needs by taking advantage of the temperature difference between the district heating water and the chamber's temperature, thereby removing the need for battery replacements.

Reference: (Gurklienė et al., 2023)

4.12.2 Proposed: Resus, Merksem, Belgium

The Belgian company Resus has developed a new sensor, the Risycor, for monitoring corrosion in district heating networks. This new apparatus is based on the classic coupon method but applies the Hall effect to measure the probe mass loss continuously, thus creating an electronic coupon method. The sensor is equipped with software that analyses the data and warns the operator about unexpected corrosion levels. In addition, the device measures temperature and pressure.

References: (Laufkotter, 2022, Resus, 2023)

4.13 SUMMARY CONCERNING MOVING HEAT

Moving heat is the core of district heating, which transforms waste heat into a useful and valuable product. There are two main options for improvement in this area: lower system temperatures and reduced operational costs. Both options directly or indirectly support decarbonisation, either by using lower heat distribution temperatures, lowering construction costs, or lowering operating and maintenance costs.

There are several network configurations other than the traditional third generation of district heating (3GDH). The driving force behind new configurations is decreased system temperatures, however, there is no standardised technology yet.

5 Storing heat

Thermal storage breaks the time dependency between the supply and demand of heat. The time scale for thermal storage ranges from a day to a season. This implies that the heat supply can be optimised despite variations in demand. With a seasonal storage size of about 25% of the annual demand, seasonal variations can be completely levelled.

Thermal storage can be categorised into low-temperature storage and high-temperature storage or by the storing solution, such as aquifers, boreholes, mines, tanks, pits, rock caverns, distribution pipes, buildings, and other solutions. These nine storage options are presented below through nine different possibilities. The locations of the cases concerning storing heat are shown in Figure 17.

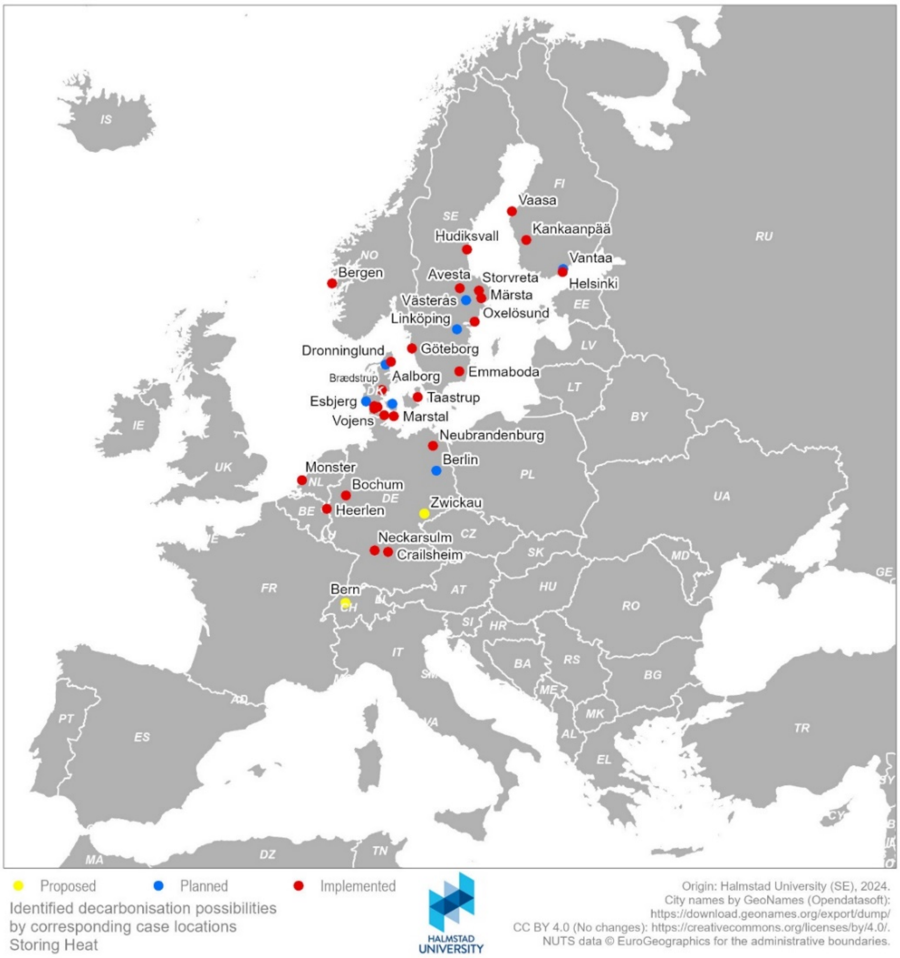

Figure 17. Map showing the locations of cases in the database concerning storing heat.

References: (Gadd and Werner, 2021), (Kallesøe et al., 2019).

Link:
https://daces.dk/daces-rapport-om-energilagring-i-danmark-2023/

5.1 AQUIFER STORAGES

Aquifer thermal energy storage (ATES) is an open system for storing heat where the groundwater is heated and cooled. ATES can occur via the injection and later reproduction of hot water in aquifers in both shallow and deep geological formations. Deep aquifers provide an option for high-temperature heat storage with injection temperatures above 60°C.

The technology for aquifer storage has been available for more than 25 years and can be used for both heating and cooling. Aquifer heat storage is a slow-reacting system because the heat needs to come up from a large depth and the pipe networks must be heated up. To minimise start-up losses and heating losses, it is recommended to use heat storage to meet base loads. This allows the heat storage to run almost continuously. Furthermore, the recovery efficiency can be increased by extracting as much heat as possible in the period immediately after storing the heat. Day and night storage could also increase seasonal recovery efficiency.

5.1.1 2005: Neubrandenburg, Germany

In Neubrandenburg, where a gas and steam turbine power plant with an electrical output of 77 MW is operated, the deep subsurface serves as thermal energy storage. In summer, excess heat from the power plant, which would otherwise have been dissipated by the plant's cooling tower, is injected into the underground. For this purpose, water at approximately 45°C is taken from a 1,200 m deep well (cold storage side) and injected into another well after heating (warm storage side). The distance between the wells is about 1,300 m. Due to the injection of warm water, an artificial geothermal zone is formed.

In winter, the direction of the water flow in the system is reversed. The heat extracted from the warm storage side has a temperature of approximately 85°C at the beginning of the extraction period and almost 75°C by the end of the extraction period. The heat is fed into a low-temperature system where it displaces the operation of the gas burners in peak-load boilers.

Link:
https://www.gtn-online.de/en/projects/aquifer-heat-storage-for-a-gas-and-steam-turbine-power-plant-in-neubrandenburg/

5.1.2 2009: Arlanda Airport, Stockholm, Sweden

The world's largest aquifer storage unit is used to cool and heat Stockholm Arlanda Airport, which requires as much heat as a town of 25,000 residents. Since the summer of 2009, ATES has helped dramatically reduce heat usage on site. The groundwater is extracted from the aquifer in the boulder ridge, known as Brunkebergsåsen, where the groundwater storage units are divided into hot and cold sections.

During the summer, cold water is pumped into the airport's district cooling network. As the water runs through the system, it is heated up; when it returns to the aquifer storage unit, it has a temperature of around 20°C. The heated water is then pumped underground and used in the winter to melt snow on the aircraft parking stands and to preheat the ventilation air in buildings. No groundwater is used in the process. Using ATES, the airport has reduced its annual heat usage by 19 GWh. As a result, large amounts of green electricity and biofuel have been freed up and can now be used by other companies.

Links:
https://www.swedavia.com/about-swedavia/the-aquifer/
https://www.power-technology.com/marketdata/arlanda-airport-aquifer-thermal-energy-storage-system-sweden/?cf-view
https://www.alfalaval.com/media/stories/industries/swedish-air-traffic-hub-obtains-substantial-energy-savings/
https://www.energi-miljo.se/akvifar-en-bra-affar-for-arlanda/

5.1.3 2012: NIOO KNAW and Koppert Cress, Monster, Netherlands

In the Netherlands, an ATES concept in combination with 2 km deep geothermal wells allows for heat to be used directly for heating about 100 hectares of agricultural land. Three geothermal heat sources (doublets) are in operation, and the temperature provided by the geothermal heat source is 92°C. The geothermal wells have surplus heat in summertime which can be stored by using an ATES system. The ATES system design comprises two wells (one doublet) that store heat in an aquifer at a 300–400 m depth.

Link:
https://www.heatstore.eu/national-project-netherlands.html

5.1.4 Proposed: Forsthaus, Bern, Switzerland

This pilot project in Bern, Switzerland, involves storing excess heat from the nearby CHP generation Forsthaus site in an ATES system and expanding the existing district heating network. The CHP generation site, which is operated by the local utility company Energie Wasser Bern, comprises a combined-cycle plant, a waste-to-energy plant, and a wood-fired power station for electricity and heat generation. For the pilot heat storage system, an exploration well about 500 m deep will be drilled to reach the Lower Freshwater Molasse (USM). The completed system is intended to store 7–10 MW of thermal heat with a maximum storage temperature of 120°C. A similar project in Geneva is the development of an ATES system connected to the waste-to-energy plant located in Cheneviers, Canton of Geneva. The system temperature is at least 50°C.

Qualitative results for the planned ATES system should be available by the end of 2023, and the system is planned to be integrated into the energy centre by 2026 at the earliest.

Links:
https://www.heatstore.eu/national-project-switzerland-bern.html
https://www.heatstore.eu/national-project-switzerland-geneva.html
https://www.thinkgeoenergy.com/pilot-project-in-bern-switzerland-explores-geo-storage-of-heat-from-waste-disposal/

5.2 BOREHOLE STORAGE

Borehole thermal energy storage (BTES) is a closed system for storing heat. It is mostly used for low-temperature applications, although it also has some high-temperature applications (>50°C). The underlying principle of BTES is to heat and then cool the subsurface by circulating a fluid in borehole heat exchangers, which consist of plastic U-tube pipes installed in closed-loop boreholes filled with a sealing grout. The distance between the boreholes is typically 2–5 m and the BTES is normally limited to boreholes of approximately 20–200 m depth. BTES can be used in most locations. Moreover, it is easy to construct and requires limited maintenance. Due to the relatively low heat transfer coefficient, BTES does not react very fast to changes in heat supply and demand.

References: (Malmberg, 2017), (Jodeiri et al., 2022)

5.2.1 1997: Amorbach, Neckarsulm, Germany

The first German solar-assisted district heating system was constructed in 1997 in Neckarsulm-Amorbach. In 2016, the BTES consisted of 528 boreholes (Gehlin, 2016). Its rectangular storage shape allows for future extension according to the expansion of the residential area. Each borehole is equipped with double U-pipes made of polybutene (PB). This is one of the pipe materials with the highest life expectancy (50 years) for a temperature of 85°C at 10 bar. The boreholes are grouted with a mix of bentonite, sand, cement, and water. The thermal insulation consists of 200 mm thick polystyrene covered with 2–3 m of soil. The heat distribution network is directly coupled to the storage. Two buffer tanks, 100 m^3 each, charge the storage using solar collectors and work as short-term storage for handling peak loads. Depending on the required temperature, heat is supplied to the buildings through the duct storage or the buffer tanks, while peak loads are met by a gas condensing boiler.

5.2.2 2007: Drake Landing Solar Community, Okotoks, Canada

The Drake Landing Solar Community in Okotoks, Alberta, Canada, utilises a solar thermal system with borehole seasonal storage to supply space heating to 52 energy-efficient detached homes through a district heating network. The local climate is cold (5,200 degree-days). The solar heat captured by 2,293 m^2 of flat-plate collectors mounted on the roofs of detached garages is stored in the soil. Once it is needed for space heating, it is extracted and distributed through a district heating system to each home in the subdivision. Independent solar domestic hot water systems are installed in every house and are designed to meet more than 50% of the water heating load.

The seasonal storage utilises approximately 34,000 m^3 of earth and a grid of 144 boreholes, each 35 m deep with single U-tube heat exchangers. The boreholes are plumbed in 24 parallel circuits, each with six boreholes coupled in series, which enables thermal stratification in the storage volume. The BTES field is covered with extruded polystyrene (XPS) insulation. The system is configured to maintain the centre of the field at the highest temperature to maximise the heating capacity and the outer edges at the lowest temperature to minimise heat losses. A short-term thermal storage of 240 m^3 of water is used to interconnect the collection, distribution, and seasonal heat storage subsystems. This case is on the same site as case 7.6.2.

Reference: (Sibbitt et al., 2012)

Link:
https://www.districtenergy-digital.org/districtenergy/library/item/fall_2022/4049842/

5.2.3 2008: Hirtenwiesen, Crailsheim, Germany

A new residential area connected to a solar collector system and duct heat storage was built in Crailsheim, Hirtenwiesen, Germany, in 2007. The heat storage, a high-temperature BTES installation consisting of 80 boreholes, was completed in 2008. Double U-pipes of high-pressure cross-linked polythene PEX (PEXa) were installed in the boreholes delivered by the company RAUGEO. PEXa collectors from RAUGEO have a temperature resistance of 95°C (Mangold and Schmidt, 2007). The storage is insulated with foam glass gravel and covered by water-protecting foil and a drainage gravel layer. In the upper part (5 m), groundwater flow was detected. Hence, the bottom of the boreholes was grouted with thermally enhanced material while the upper parts were grouted with a less conductive material.

A buffer water tank works as a short storage solution for the solar collectors. The heat from the seasonal part can be transmitted through the district heating network to the diurnal part, either directly or via a 530 kW heat pump. While the storage temperature varies between 20–50°C, the heat pump always supplies hot water at 60°C. With the use of the heat pump, the storage temperature can be kept lower, thereby decreasing heat losses.

5.2.4 2010: Xylem Water Solutions AB, Emmaboda, Sweden

The BTES in Emmaboda works both as an energy research project and as a system to increase the energy efficiency of the Xylem Water Solutions AB plant in Emmaboda. The BTES has been operating since 2010 and was initially designed to work without a heat pump. As a result, rather high storage temperatures were initially required (Nordell et al., 2016). The borehole field of 140 boreholes is divided into seven individually controlled sections with 20 wells each. The sections open or close individually depending on the storage temperature during injection and extraction procedures. This maintains good thermal stratification in the storage volume with higher temperatures in the centre.

The storage temperature increased to around 45°C by September 2015, however, it has been clarified that the target storage temperature of 55°C will not be reached. The supply temperature to the storage, which was assumed to be 60°C during the design phase, is much lower in reality, rarely exceeding 50–55°C. Nevertheless, the storage, which is mainly charged during the summer and discharged during the winter without any heat pumps, has a great news value and has practically no negative environmental effects.

References: (Ramstad et al., 2023), (ACUÑA et al., 2021)

5.2.5 2012: Brædstrup, Denmark

The Brædstrup district heating network in Denmark is supplied by the Brædstrup Totalenergianlæg (Brædstrup Total Energy Plant), a natural gas-fired CHP unit. Brædstrup Totalenergianlæg was in 2007 the first natural gas-fired CHP plant to be combined with a solar thermal system. In 2011–2012, the solar plant was extended and a pilot borehole storage of 48 boreholes was added to the system. The system was also equipped with a 5,000 m^3 buffer tank, a 1 MW heat pump, and a 10 MW electric boiler. Further system extensions have already been planned. The full-scale borehole storage system will be installed around the pilot storage but with separate transmission lines. Thus, the two storage solutions will be hydraulically separated, and are preliminary planned to comprise 432 boreholes.

The borehole setup of Brædstrup Totalenergianlæg is based on the borehole setup used in Crailsheim, Germany. The borehole heat exchanger design is based on the design used in Crailsheim, which uses double U-tubes of the RAUGEO PEXa type. The boreholes are connected in 16 parallel flow lines with six boreholes in series and a pressure drop of approximately 2.0 bars in each line. The boreholes are grouted with HDG Thermo HS with a thermal conductivity of around 1.44 W/(m K). The storage is insulated with cockles, which are available in Denmark in large quantities.

Reference: (ACUÑA et al., 2021)

Link:
https://www.districtenergyaward.org/braedstrup-fjernvarme/

5.3 MINE STORAGE

Mine thermal energy storage (MTES) uses the groundwater present in abandoned mines as a carrier for storing heat. The storage cost can be reduced by reusing pre-existing voids. MTES is mostly used for low-temperature applications (20–45°C), but some high-temperature applications also exist.

Reference: (Kallesøe et al., 2019)

5.3.1 2008: Mijnwater, Heerlen, the Netherlands

The Mijnwater project in Heerlen, the Netherlands, utilises mine water for heat extraction in Germany and the Netherlands. In this example, a completely flooded and no longer accessible mine was accessed using directional drilling technology to use the mine water as an energy source for a heat pump.

Five wells were drilled to the stone drifts. The two hot wells in the northern part of Heerlen have a depth of 700 m for the extraction of hot water with a temperature of about 28°C. The two cold wells in the southern part of Heerlen have a depth of 250 m for the extraction of cold mine water with a temperature of about 16°C. The fifth well, which is in the middle part of Heerlen with a depth of 350 m, is used to inject the cooled hot and warmed cold mine water with intermediate temperatures of 18–22°C. Through a three-pipe mine water distribution network of 7 km, the so-called mine water backbone, the mine water from the wells is provided to the energy stations of the connected buildings (Verhoeven et al., 2014).

This case is on the same site as case 7.4.1.

Link:
https://mijnwater.com/en/

5.3.2 2020: Bochum, Germany

The German HEATSTORE sub-project aims to create a technically and fully functional seasonal MTES pilot demonstration plant for the reuse of energy from the abandoned hard coal mine Markgraf II in Bochum. The emphasis is on the extended operating and monitoring phase of the HEATSTORE project. The plant began to operate in 2020. This pilot plant uses 20°C warm mine water which originates from the mine drainage of the RAG AG from a depth of 570 m. The conceptual idea is based on the storage of seasonal unutilised surplus heat during the summer from the solar thermal collectors in the mine layout. The stored heat can then be used during the winter for heating the buildings of the International Geothermal Centre (GZB).

Links:
https://www.heatstore.eu/national-project-germany.html
https://www.heatstore.eu/documents/HEATSTORE_Webinar_28%20Sept%202021_The%20MTES%20project%20in%20Bochum,%20Germany.pdf (PPT in German)

5.3.3 Proposed: West Saxon University, Zwickau, Germany

A deep mine water project is currently being investigated at the West Saxon University of Zwickau, where mine water with a temperature of 26°C is planned to be extracted from a depth of 625 m (Hahn et al., 2019).

Link:
https://www.thinkgeoenergy.com/mine-water-targeted-for-geothermal-heating-in-saxony-anhalt-germany/

5.4 TANK STORAGE

Tank storage refers to storing heat or cold in a container that holds liquids, compressed gases, or other mediums. It is mostly used for daily thermal storage by using water as the storage medium.

An inventory of implemented tank heat storage solutions in Sweden is provided by (Eriksson, 2016). There was a volume of 900,000 m^3 available for heat storage in the examined district heating systems. A total of 167 systems have been analysed; these systems represent 97% of the annual heat sales in Swedish district heating systems. The size of the analysed heat storage solutions varies from 100,000 m^3 to only 50 m^3. Out of the 167 analysed systems, 104 have installed storage capacity. This represents 77% of the annual heat sales and indicates that most of the delivered district heating in Sweden utilises heat storage.

5.4.1 Planned: Aalborg, Denmark

Aalborg Forsyning has just entered a contract with the Swedish Rodoverken for the delivery of a 200,000 m³ heat tank storage. This is an investment of approximately DKK 400 million. The heat storage will consist of four steel tanks located in Norbis Park, which is an area owned by Aalborg Forsynin near the Nordjyllandsværket. When the four tanks are fully charged, they will contain the equivalent of 625 households' annual heat consumption. The tanks are expected to start operating in 2025.

Link:
https://aalborgforsyning.dk/privat/nyheder-og-presse/seneste-nyheder/18-10-2022-investering-i-stort-varmelager-skal-sikre-billig-fjernvarme-i-aalborg-kommune/

5.4.2 Proposed: GigaTes, Gleisdorf, Austria

The GigaTes project will investigate three Austrian sites with respect to the main challenges of district heating, including construction, geology and geophysics, materials, operating characteristics, economic aspects, and public acceptance. The project includes underground tank thermal energy storage. The hybrid tank storage has been built. The maximum depth of the diaphragm wall is 50 m (Helden et al., 2021).

Link:
https://www.gigates.at/index.php/en/gigates/project

5.5 PIT STORAGE

Pit thermal energy storage (PTES) consists of using a large water reservoir to store thermal energy. The reservoir is lined with a waterproof plastic lining to retain heat and prevent water from leaking into the surrounding soil. The top of the storage is covered by a floating insulating cover used for retaining the heat and keeping rainwater from entering the storage. Temperatures up to approximately 90°C can be stored. Pit storage offers the same flexibility as BTES.

Denmark has built several pit heat storage solutions connected to solar heating systems. In larger district heating systems, a pit can be a cheap energy source that meets peak loads and reduces the price of heating. Heat storage pits combine three existing technologies: landfills, hot water tanks, and offshore steel technology. When larger heat storage is required, PTES is very cost-effective. A review of pit thermal energy storage can be found in (Helden et al., 2021). In the HeatStore state-of-the-art report, the main advantage of PTES is the possibility of quick charging and discharging. If the ground conditions are optimal, the construction costs are low. One of the disadvantages is the high space demand since PTES requires large areas without infrastructure. High groundwater levels and poor soil conditions directly affect the construction costs.

References: (Kallesøe et al., 2019), (Goodstein and Haukursson, 2021), (Sifnaios et al., 2023)

5.5.1 2004: Marstal Fjernvarme, Marstal, Denmark

Marstal Fjernvarme started to construct two pit storage solutions, SUNSTORE 2 (10,000 m³) at 67 EUR/m³ in 2003 and SUNSTORE 4 (75,000 m³) in 2014. The first pit storage was completed in 2004 and is not in use any longer. The temperatures are between 30–90°C. The storage space is covered with foil, as well as a new collector area of 15,000 m² (added to the original 18,000 m²), a 4 MW wood chip boiler, and a 1.5 MW electrical heat pump. Together, they supply the town of Marstal with 100% renewable energy. Additionally, an organic Rankine cycle produces electricity for the public grid. The cover foil in Marstal is made of a new material that contains polythene foam and a high-density polythene lining. It is supposed to reduce heat loss at the top side by 60% compared to the small existing storage.

This case is on the same site as case 7.6.1.

Links:
http://co2mmunity.eu/wp-content/uploads/2019/03/Factsheet-Aer%C3%B6-Marstal.pdf
https://www.cfms-sols.org/sites/default/files/Actes/3351-3354.pdf
https://solarthermalworld.org/news/denmark-23-mwth-cover-55-heat-demand-1500-households/

5.5.2 2014: Dronninglund Fjernvarme, Dronninglund, Denmark

Through the SUNSTORE 3 project in Dronninglund, PTES was constructed in 2013 and it started operating in 2014. The size of the storage is 60,000 m³ with a cost of 38 EUR/m³ of storage capacity. The PTES can store 5.4 GWh of heat, and it has a charging and discharging capacity of 26 MW. The temperatures range between 10 and 89°C. The Dronninglund seasonal thermal storage is connected to the district heating grid via a heat pump. This allows for lower storage temperatures throughout the year, which reduces heat losses. The PTES has now reached a heat storage efficiency of more than 90%. This case is on the same site as case 7.6.5.

Reference: (Sifnaios et al., 2023)

Link:
https://solarthermalworld.org/news/seasonal-pit-heat-storage-cost-benchmark-30-eurm3/

5.5.3 2015: Gram Fjernvarme, Gram, Denmark

Gram started to construct a PTES in 2014 which came into operation in 2015. The size of the storage is 125,000 m³ with a cost of 34 EUR/m³ of storage capacity. The PTES can store 12.1 GWh of heat, and it has a charging and discharging capacity of 30 MW. The storage temperatures range between 20 and 90°C. The PTES allowed the company to increase the share of solar heating in the annual district heating supply from 16% to 61%. This case is on the same site as case 7.6.3.

Links:
https://stateofgreen.com/en/solutions/large-scale-solar-heating-and-seasonnal-heat-storage-pit-in-gram/
https://r-aces.eu/use_case/gram-fjernvarme-district-heating/

5.5.4 2015: Vojens Fjernvarme, Vojens, Denmark

Vojens Fjernvarme started to construct a PTES system in 2014 which came into operation in 2015. The storage is excavated in an old sand pit. The size of the storage is 200,000 m^3 with a cost of 38 EUR/m^3 of storage capacity. The PTES can store 12.2 GWh of heat, and it has a charging and discharging capacity of 12 MW. The temperatures range between 40 and 90°C. When it was commissioned in 2015, it was the largest heat storage system in the world. This case is on the same site as case 7.6.4.

Links:
https://stateofgreen.com/en/solutions/world-largest-thermal-pit-storage-in-vojens/
https://deepresource.wordpress.com/2020/12/16/district-heating-with-seasonal-storage-in-vojens-denmark/

5.5.5 2017: Toftlund Fjernvarme, Toftlund, Denmark

Toftlund started to construct a pit storage system in 2016 which came into operation in 2017. The size of the PTES is 85,000 m^3 with a cost of 48 EUR/m^3 of storage capacity. The PTES can store 6,885 MWh of heat, and it has a charging capacity of 18 MW and a discharging capacity of 8 MW. The temperatures range between 20–90°C.

Link:
https://www.heatstore.eu/documents/20201028_DK-temadag_Ramb%C3%B8ll%20PTES%20project.pdf

5.5.6 2023: VEKS, Høje Taastrup, Denmark

This PTES is positioned in a former agricultural area near Bondehøjvej, just north of the Holbæk motorway in Høje Taastrup. The storage volume is 70,000 m^3. The PTES can store 3.3 GWh of heat, and it has a charging and discharging capacity of 30 MW. This project represents the first time this type of pit heat storage will be used as short-term storage in a very large district heating system in Denmark.

The PTES liner is a new type of polypropylene (PP) liner which was developed through the Austrian innovation project GigaTES and has an expected life of 33 years at 95°C. The total heat loss from the storage, including from the lid, is expected to be 8–9% annually. The thermal storage was put into operation in February 2023. It is expected to provide added value to the Greater Copenhagen district heating system and contribute to the green transition.

References: (Bruus and Sørensen, 2019), (Wetzel and Bruss, 2023)

Links:
https://planenergi.eu/wp-content/uploads/2022/07/Heat-pit-storage_folder-2022_uk.pdf
https://www.veks.dk/en/focus/still-the-key
https://heatstore.eu/documents/20201028_DK-temadag_H%C3%B8je%20Taastrup%20Fjernvarme%20PTES%20project.pdf

5.6 ROCK CAVERN STORAGE

In rock cavern thermal energy storage (CTES), heat is stored as hot water in an underground rock cavern. Alternative structures for CTES include abandoned mines, which were presented in Section 5.3.

Link:
https://hal-ineris.archives-ouvertes.fr/ineris-03319052/document

5.6.1 1981: Avesta, Sweden

A district heating system has been installed with a hot water accumulator blasted into rocks near the city of Avesta. With a volume of 15,000 m^3 and a depth of 25 m, the Avesta CTES was built in 1981 for short-term energy storage of the heat generated at an incineration plant. The time for spontaneous cooling is extremely long (>10 years). This rock cavern is still in use and is operated by Adven.

Reference: (Rehbinder, 1985).

5.6.2 1983: Storvreta, Sweden

The Lyckebo rock cavern has an excavated volume of 100,000 m^3 which is used for storing up to 5.5 GWh/year of heat with a temperature between 60°C and 90°C. This CTES is a seasonal thermal storage system and is part of the local Storvreta district heating system just north of Uppsala. Initially, this heat storage system was connected to a solar collector field that was later dismantled.

One possible approach for meeting peak heat demand with this CTES is elaborated in case 9.2.1.

References: (Brunström et al., 1988), (Åsberg, 2011)

5.6.3 1988: Oxelösund, Sweden

The oil rock cavern in Oxelesund, which has a volume of 200,000 m^3, was planned to be used for thermal energy storage. Due to economic considerations at the time, the oil in the cavern was not going to be removed before using the cavern for thermal storage. Experiments were carried out in model rock chambers in a laboratory. The tests showed low levels of residual oil in the water. In trials with pilot plate heat exchangers in oily water, no significant deterioration of the heat transfer was noted. This was unexpected since it was feared the heat exchangers would become coated with oil. Nevertheless, this CTES was not used.

Reference: (Bergström and Ekengren, 1993)

5.6.4 2018: Hudiksvall, Sweden

The district heating network in the Swedish town of Hudiksvall has been gradually expanded since its inception in 1974. Currently, Adven supplies local heat to around 700 properties in the town. This solution includes the use of two rock caverns for heat storage. These rock caverns were previously used for fuel oil storage.

The CTES under Köpmanberget in Hudiksvall has two water rooms, each with a volume of 90,000 m^3. Heat is supplied from a co-generation plant to heat the storage and create a thermal layer. The CTES can store 4.1 GWh of heat. Every water room has a length of 200 m, a height of 25 m, and a width of 18 m. One room stores cold water at 45°C, while the other room stores hot water at 95°C. Using two rooms can solve the issue of heat conduction from warmer water to colder water, which is a risk in vertical storage tanks.

The use of this heat storage system as an efficient solution to meet peak loads is discussed in case 9.2.2.

Reference: (Mårtensson, 2020)

Links:
https://adven.com/se/fjarrvarme/hudiksvall/
https://energiforsk.se/media/27147/bergrumslagret-i-hudiksvall.pdf
https://www.energi.se/artiklar/har-samlas-fjarrvarme-under-berget/

5.6.5 2020: Vaasa, Finland

Vaasa started storing energy in CTES under the Vasklot power plant in 2020. The CTES can be heated in four days. The CTES system comprises two rock rooms with a total volume of 210,000 m^3 and a depth of 30 m. The temperatures are 45°C in the lower end and 90°C in the upper end of the CTES according to the figure in the link below. The rock rooms were blown up in the 1950s to store fuel oil; since the 1990s, they have been unused and waterlogged.

Link:
https://svenska.yle.fi/a/7-1414455

5.6.6 2021: Helsinki, Finland

The Helen company started to use Finland's largest thermal storage system in 2021. The CTES is located under Blåbärslandet. The effective storage volume is 260,000 m^3 and the energy storage capacity is approximately 11.5 GWh. The charging and discharging capacity is 120 MW. The CTES caves serve the district heating network's customers by smoothing out consumption peaks throughout the year. The storage saves 21,000 tonnes of carbon dioxide emissions per year.

Link:
https://www.helen.fi/sv/uutiset/2020/mustikkamaa

5.6.7 Planned: Västerås, Sweden

Mälarenergi plans to use a former oil storage cavern for thermal storage linked to a district heating system. The rock cavern was emptied in the 1980s and has remained vacant ever since. Mälarenergi has decontaminated the storage facility and will fill it with hot water with temperatures up to 95°C. This will allow the company to optimise electricity and heat generation and use the cavern as a thermal reservoir to meet peak loads. In essence, Mälarenergi is building a giant underground thermal storage which will be one of the largest of its kind in Europe.

The CTES consists of three cavern spaces with a total volume of 300,000 m^3. The energy capacity will be about 13 GWh with a rated power capacity of up to 90 MW. The CTES is planned for operation in 2024.

The use of this heat storage solution to meet peak heat demand is elaborated in case 9.2.3.

Reference: (Nohrstedt, 2022)

Links:
https://www.nyteknik.se/premium/kraftvarmen-den-dolda-raddaren-i-elsystemet-7037976
https://www.energi-miljo.se/har-byggs-europas-storsta-hetvattenlager/
https://www.bbc.com/news/business-65098792

5.6.8 Planned: Vantaa, Finland

The Vantaa Energy Cavern Thermal Energy Storage (VECTES) is a seasonal energy storage solution for harnessing the warmth of summer during cold winter days. The facility will be the world's largest CTES with 1,000,000 m^3. It will have an energy storage capacity of 90 GWh. The storage of hot water at an exceptionally high temperature of 140°C increases the storage capacity while being cost-efficient. The application is very competitive and scalable to other regions, thus contributing to the decarbonisation of energy systems across Europe. The planned completion of the project is in 2026.

References: (Vantaan Energia, 2021), (Olofsson, 2021)

Link:
https://www.vantaanenergia.fi/en/carbon-negativity-2030/heatstorage/

5.6.9 Planned: Helsinki, Finland

Helen and Skanska have started a joint project on an energy warehouse in Kronbergsstranden. A large seasonal energy storage system is being built in the caves under Kronberget, which were previously used by Shell for oil storage. The caves were first emptied in 2007 and cleaned in 2008–2009. After that, the caves were reused, emptied, and cleaned for the second time in 2010–2011. The caves have a total volume of 300,000 m^3 and are located approximately 50 m below sea level. One of the two caves is about 18 m wide, while the other cave is about 16 m wide. Both caves are about 30 m high. The larger cave is 326 m long; the smaller one is 245 m long. The storage building phase began in 2022.

Links:
https://www.helen.fi/sv/uutiset/2018/s%C3%A4songslager-f%C3%B6r-energi-planeras-i-kronbergsstrandens_grottor
https://www.helen.fi/sv/uutiset/2022/bygget-av-ett-sasongslager-for-energi-i-kronbergsgrottorna-har-borjat

5.6.10 Proposed: Skanska, Stockholm, Sweden

Skanska TES has proposed a concept in which heat and cooling can be stored in the same rock facility under a city. Such a thermal energy storage system can meet the city's heating and cooling needs, including balancing variations in energy demand between daytime and night-time, weeks, months, and seasons. The storage consists of a spiral of tunnels linked by connecting tunnels. Holes are drilled between the tunnels so that the surrounding rock can be heated or cooled by circulating water. The top of the storage is approximately 100 m below the surface. The storage has an energy capacity of 50 GWh and a diameter of 200 m. The thermal efficiency in such a system is nearly 100% because it has minimal heat losses. The total annual energy turnover rate is 3–10 times the seasonal storage capacity and varies depending on the external district heating and cooling system.

Reference: (Skanska Sverige AB, 2018)

5.7 HEAT DISTRIBUTION PIPE STORAGE

The district heat network control strategy can be employed to utilise the storage capabilities of the network (Kouhia et al., 2019). The storage potential of district heating pipes has been investigated in several district heating systems in Sweden and China (Zhang et al., 2022). The storage capacities of Swedish DH networks are less than 0.8% of the daily heating demand when considering a 10°C temperature increase in the supply network. By contrast, due to the larger pipes used in Chinese DH systems, the equivalent Chinese index is 4% of the daily heating demand.

Pipe-based heat storage is limited by the risk of low-cycle fatigue in pre-insulated steel pipes from frequent, large temperature changes causing repetitive plastic deformations. More information about this long-term risk with high-temperature amplitudes can be found in (Kim and Weidlich, 2017) and (Hay et al., 2021).

5.7.1 2017: Bergen, Norway

Norsk Energi has upgraded the BKK district heating network in Bergen with a new automation system that includes new control systems for the boiler houses. In the district heating network, there is a booster pump that starts and stops automatically according to the energy load on the district heating system. The steering system can be used to minimise fossil fuel usage at the peak load by accumulating heat from the district heating network. According to the link below, the supply temperature in the network can be increased by about 20°C without the thermal strains being unacceptably high. However, as mentioned above, these temporarily high temperatures can cause low-cycle fatigue.

The BKK network contains about 5,000 m^3 of water. An increase of 20°C in the supply temperature in the network is equivalent to storing 50 MWh of heat. This helps reduce the difference between the heating load at night and during the day.

Link:
https://energi.no/en/advanced-control-system-for-district-heating-plant-at-bkk-district-heating-company-in-bergen

5.8 BUILDINGS AS HEAT STORAGE

Buildings can be utilised as short-term thermal energy storage (TES). Active storage in the building structure, including building elements such as walls, floors, and ceilings, can be designed to actively charge and discharge heat from the elements. Heat storage can be achieved by systematically making small changes to the setpoints for space heating. Daytime heat deliveries can be moved to night-time deliveries by reducing the daytime setpoints and increasing the night-time setpoints. Because of the high thermal inertia of buildings, the variations in indoor temperature will be very small.

5.8.1 2015: Gothenburg, Sweden

In 2010–2011, the ability of five residential buildings with 3–5 stories to function as thermal energy storage units in a district heating system was tested in Gothenburg, Sweden. The five buildings were categorised as light or heavy based on their thermal mass. A light building typically has a core of steel or wood, which results in a low heat storage capacity. A heavy building typically has a core of concrete, which results in a high heat storage capacity.

All five buildings were constructed between 1939 and 1950 and have an annual heating demand of approximately 150 kWh per square metre of floor area. The light building had a lower potential for being utilised for short-term TES than the heavy buildings. The four heavy buildings could store heat at 63°Ch by adjusting the outdoor temperature signal from +7°C to -7°C without jeopardising the quality of service.

Reference: (Kensby et al., 2015)

5.8.2 2018: Sønderborg, Denmark

The study investigated the potential of thermal building mass for storage in district heating systems in the city of Sønderborg. The building stock was characterised by six archetypes that represented 60% of the single-family houses in the area. The buildings were evaluated based on three indicators: the thermal autonomy, which was determined through a heat supply cut-off during which the internal temperature did not fall below 18°C, the savings in heating demand compared to the reference case, and the economics of the system. It was concluded that the highest potential for utilisation of building thermal mass was provided by houses built after the 1980s, which have well-insulated building envelopes and thus lower transmission losses. Furthermore, the thermal autonomy potential was better described by the total heat loss coefficient of the building envelope than the time constant during cold and cloudy weather conditions. This is because a building's heat losses were found to have a more dominating effect than its thermal mass.

The economic savings in operational costs of the district heating system of the city of Sønderborg were in the range of 0.7–4.6% without considering the cost of smart controls. The load shifting enabled by thermal mass storage allows for larger load factors of capital-intensive technologies with low operating costs, such as central heat pumps.

Reference: (Dominković et al., 2018)

5.9 OTHER HEAT STORAGE

Beyond the eight storage possibilities presented in the previous sections, other storage solutions have been recently implemented or planned. The three cases presented below concern sand batteries, cracked bedrocks, and molten hydroxide.

5.9.1 2022: Kankaanpää, Finland

A sand battery is a high-temperature thermal energy storage solution that uses sand or a sand-like material as its storage medium. The term sand battery was introduced to a large audience by a BBC News story published on 5 July 2022.

The first commercial sand battery in the world is in a town called Kankaanpää, western Finland. It is connected to a district heating network that serves residential and commercial buildings such as family homes and the municipal swimming pool. The district heating network is operated by the energy utility Vatajankoski.

Link:
https://polarnightenergy.fi/sand-battery

5.9.2 2023: Linköping, Sweden

This pilot project on heat storage started in 2021 and the connection to storage was made in 2023. Both distributed and centred heat storage were considered. The main benefits of distributed heat storage are the low supply temperature, efficient utilisation of power, effective handling of power demand peaks, and local reservation. The main benefits of centred storage are its large capacity, low heat loss, high power during charging, and the need for only one storage place.

The Gothenburg-based Hydroc company has developed a new bedrock cracking technique. Large surface areas are created using a fracturing technique suitable for boreholes over 100 m deep. Groundwater is then circulated through the boreholes to heat or cool the bedrock.

Links:
https://energiforsk.se/media/31317/sprickva-rmelager-en-revolution-fo-r-termiska-geolager-henrik-lindsta-hl.pdf
https://www.hydroc.se/
https://www.energi-miljo.se/geotermisk-utveckling-i-linkoping/
https://www.energimyndigheten.se/forskning-och-innovation/projektdatabas/sokresultat/?registrationnumber=2020-018552
https://termoinnovation.se/projekt/underjordiskt-varmelager-med-hoga-effekter-och-temperaturer/
https://termoinnovation.se/wp-content/uploads/2024/01/slutrapport-ny-generation-underjordiskt-varmelager.pdf
https://www.energimyndigheten.se/forskning-och-innovation/projektdatabas/sokresultat/?registrationnumber=2022-200143

5.9.3 Planned: Esbjerg, Denmark

The MOlten Salts Storage (MOSS) project aims to build the first Hyme storage facility in Esbjerg, Denmark, to display and test molten hydroxide storage. The system is integrated into a thermal plant. Hot salt is pumped through the heat exchanger into the cold tank (350°C); cold salt is pumped through the electrical heaters into the hot tank (<700°C). The plant is expected to become fully operational in 2023.

Link:
https://www.hyme.energy/project/moss
https://danskfjernvarme.dk/aktuelt/nyheder/2023/naeste-generation-af-varmelagring-er-paa-vej

5.10 SUMMARY CONCERNING STORING HEAT

This chapter considered possibilities related to applying heat storage solutions in district heating systems to break the time dependence between heat supply and heat delivery. The time required for storing heat ranges from a single day to several seasons with a loading and unloading cycle of one year.

The main decarbonisation option associated with storing heat is carbon savings from breaking the time dependence between heat supply and delivery, which results in a more efficient heat supply. This implies that the heat supply can be optimised without considering variations in the heat demand, thereby eliminating the need for peak-load heat supply.

6 Removing carbon dioxide

Carbon dioxide removal (CDR) from flue gases is suggested by the (IPCC, 2022) as a key measure to achieve climate targets. The use of CDR on biomass incineration and waste-to-energy schemes allows for negative carbon dioxide emissions provided that the removed carbon dioxide is permanently stored. This is an interesting opportunity for district heating companies and is likely to be incentivised or required by regulation in the near future. In CHP plants for district heating, the flue gases from the incineration of biomass or waste are concentrated in one point, which can make CDR very effective. This also applies to biomass-intensive industries, where excess heat is commonly used for district heating.

The Swedish government announced in late 2022 a proposal to spend SEK 36 billion (€ 3,1 billion) between 2026 and 2046 on CDR from biomass combustion with storage. Similarly, the Danish government will grant DKK 8.1 billion (€ 1 billion) ; this was approved by the European Commission in early 2023 (Reumert, 2023). The first contract in this programme was awarded to Ørsted in mid-2023 (see Sub-section 6.1.3). In September 2023, the Danish government presented an agreement, with broad political support, to spend DKK 38 billion (€ 5 billion) on CDR between 2025 and 2045 (this includes the initial DKK 8.1 billion (€ 1 billion) contract). Bidding for the larger contracts in this agreement will take place in 2024 and 2025 (Fjernvermen, 2023).

There are two main processes for CDR in the context of CHP and district heating (Beiron et al., 2022): the monoethanolamine (MEA) process and the hot potassium carbonate (HPC) process. The MEA process is an amine scrubbing process that requires heat input from steam. This decreases both the power production in the turbine and, in most reported cases, the heat delivery. Heat may be recovered from the MEA process and fed into a district heating network, thereby increasing the overall efficiency. The HPC process is powered by electricity which may originate from the turbine or the grid. It is overall more efficient than the MEA process. Heat can be recovered from the HPC process as well, which means that the total heat delivery typically increases with the addition of the CDR while the power delivery decreases. With both methods, district heating is crucial to achieve good overall efficiency.

Another method to remove carbon dioxide from the fuel used in district heating is to remove the fossil content in the waste streams and redirect that content to recycling, which may involve chemical or mechanical processes. In principle, the removal is best done at the household level by proper segregation of the waste. In practice, it has proved difficult to avoid fossil plastics in general household waste. These plastics may be removed from waste intended for incineration by so-called post-sorting facilities to reduce fossil carbon dioxide emissions.

The locations of the identified cases concerning removing carbon dioxide are shown in Figure 18.

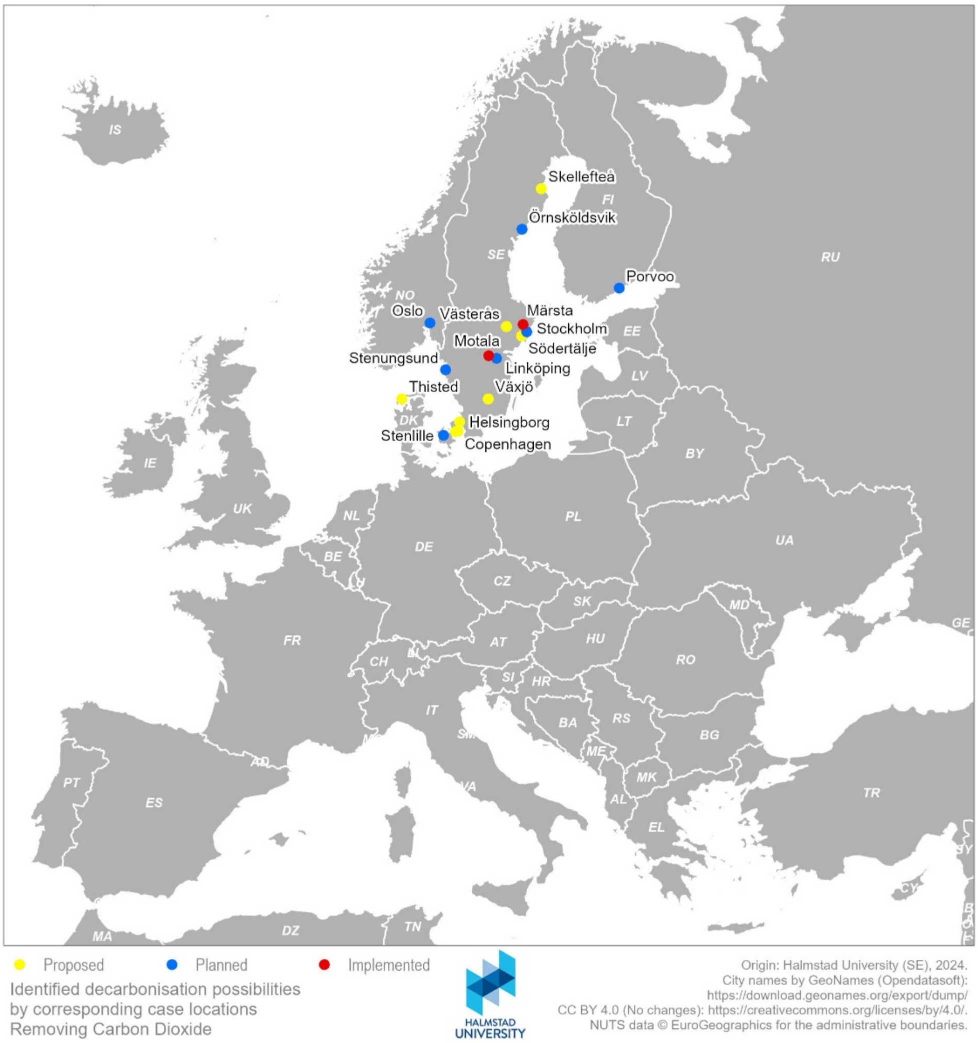

Figure 18. Map showing the locations of cases in the database concerning removing carbon dioxide.

6.1 CDR FROM BIOMASS

CDR from biomass incineration, in combination with storage, is commonly denoted as bioenergy with carbon capture and storage (BECCS). BECCS is relevant in district heating both at CHP plants and in industries that supply excess heat to district heating. The interest and efforts around introducing CDR in the district heating sector are rapidly growing, as evidenced by the cases presented below. Most of these cases concern removing carbon dioxide for permanent storage, while a few concern the utilisation of carbon dioxide for processes or products.

In (Energiföretagen, 2022), the Swedish district heating sector presents a strategy for implementing BECCS and indicates the measures needed to achieve this.

Link:
https://www.energi.se/artiklar/2023/juni-2023/har-ar-energibolagen-som-satsar-pa-bio-ccs/

6.1.1 2019: Värtaverket, Stockholm Exergi AB, Stockholm, Sweden

Värtaverket, a biomass-fuelled CHP plant in Stockholm owned by Stockholm Exergi AB, is planned to use the HPC process for full-scale BECCS. According to the plan, a facility capable of removing 800,000 tonnes of carbon dioxide yearly will be in operation in 2025. A small-scale test facility with the same HPC process has been in operation at Värtaverket since 2019. The removed carbon dioxide will be liquified and transported by boat to the Northern Sea for underground storage. Extensive heat recovery in the different process steps is planned. Early estimations indicate a total capacity of 50–55 MW of heat with temperatures of 75–80°C.

This project received a grant from the EU Innovation Fund in 2022 to help realise the plans. The project filed an application for an environmental permit for the full-scale facility in late 2022 (Wikström and Adrup, 2022) and a final investment decision is expected in 2024. A letter of intent was signed in 2023 with Saipem regarding engineering activities in connection to carbon dioxide handling.

Link:
https://beccs.se

6.1.2 2022: Sandviksverket, Växjö Energi, Växjö, Sweden

A pilot facility for CDR was installed in mid-2022 at Sandviksverket, a biomass-fuelled CHP plant owned by Växjö Energi AB. The technique used, known as AMP/DMSO (Karlsson et al., 2021), is amine-based but differs from the standard MEA process by being non-aqueous. The technology has been developed by researchers from Lund University and is expected to be more energy-efficient than the standard MEA process. The project, which is a cooperation between Lund University, Granitor, Sysav, Öresundskraft, and Växjö Energi, received funding from the Swedish Energy Agency in 2022. The potential for CDR at Sandviksverket is noted to be 200,000 tonnes yearly for a full-scale facility, which may become operational by 2027 according to current plans.

There are plans to test the same technique at two waste-to-energy CHP plants: Filbornaverket in Helsingborg (Öresundskraft AB) and Sysav in Malmö.

Link:
https://www.veab.se/om-oss/press/pressmeddelanden/2021/vaxjo-energi-forst-ut-med-att-testa-ny-teknik-for-att-fanga-in-koldioxid/

6.1.3 Planned: Asnæs and Avedøre CHP plants, Copenhagen, Denmark

The Asnæs CHP plant in Kalundborg, Denmark, and the Avedøre CHP plant in Greater Copenhagen, both operated by Ørsted, will implement BECCS with a planned start of operations in 2025. By 2026, full-scale operation is expected at these plants, which can capture 430,000 tonnes of carbon dioxide yearly. The development, whose construction started in December 2023, is a consequence of Ørsted being awarded a contract of DKK 8 billion under the Danish state aid programme for CDR.

Links:

https://danskfjernvarme.dk/aktuelt/presseklip/2023/230516-dagens-overblik?link_id=f83061a8-c225-4b5e-a414-701d49cf16ee
https://danskfjernvarme.dk/aktuelt/nyheder/2023/oersted-bygger-danmarks-foerste-co2-fangstprojekt

6.1.4 Planned: Hörneboverket, Örnsköldsvik, Sweden

Hörneboverket, a biomass-fuelled CHP plant in Örnsköldsvik, Sweden, owned by Övik Energi, will serve as a carbon dioxide source for FlagshipONE, a planned e-methanol factory to be built by Ørsted in Örnsköldsvik (Bioenergi, 2023c). FlagshipONE is planned to start operations in 2025. In 2023, Ørsted announced an agreement with Carbon Clean, which will supply the CDR equipment for the operations. An amine-based process that has been refined by Carbon Clean will be used. The e-methanol will provide green fuel for shipping.

6.1.5 Proposed: Igelstaverket, Söderenergi AB, Södertälje, Sweden

A system study was performed in 2022 at Igelstaverket, a biomass-fuelled CHP plant in Södertälje owned by Söderenergi AB, to consider options for BECCS. The study compared the MEA and HPC processes and noted the potential for the removal of 500,000 tonnes of carbon dioxide yearly. In late 2022, an application for SEK 25 million was filed to the Swedish Energy Agency (Industriklivet) to be able to continue to the next phase.

Link:
https://bioenergitidningen.se/igelstaverket-ska-minska-koldioxidutslappen-med-500-000-ton/

6.1.6 Proposed: Mälarenergi, Västerås, Sweden

A preliminary study was performed in 2021 at Mälarenergi, Västerås, to implement BECCS at their CHP plant. The study was supported by a grant from Energimyndigheten (Bioenergi, 2020).

6.1.7 Proposed: Njord Carbon project, Stockholm, Sweden

Njord Carbon is a cooperation between Verdane (an international investment firm), Södra AB (a Swedish company that sells forest products), and Equinor (an international energy company headquartered in Norway). The project aims to implement BECCS into industry facilities in Södra, such as their pulp industry, which is a major supplier of excess heat to nearby district heating systems (Bioenergi, 2023a). Equinor brings in expertise in carbon dioxide storage, which is considered the main solution for the removed carbon dioxide, although circular usage through new products will also be examined.

6.1.8 Proposed: Amagerværket, Copenhagen, Denmark

Amagerværket, a biomass-fired CHP plant in Copenhagen owned by HOFOR, has announced plans to capture up to 900,000 tonnes of carbon dioxide annually. HOFOR was awarded DKK 50 million in late 2023 to support the preparation of an application for a grant under the Danish CDR state aid programme. Following a positive response to the application, a CDR facility could be commissioned in 2028 or 2029.

Link:
https://danskfjernvarme.dk/aktuelt/nyheder/2023/hofor-goer-klar-til-at-fange-co2-paa-amagervaerket?link_id=5c634915-6142-40c1-9907-289e8ea58c1a/

6.2 CDR FROM WASTE-TO-ENERGY

Depending on the proportions of fossil content to biogenic content in the waste streams, waste-to-energy CDR and subsequent storage will also contribute to negative carbon dioxide emissions, albeit less than in the case of biomass incineration. Despite the fossil carbon dioxide content, this process is also commonly denoted as BECCS. The Danish district heating sector presented in (Fjernvarme, 2023) a list of measures that the Danish government should consider to facilitate CDR from waste and biomass incineration.

6.2.1 2021: Kraftvarmeværk Thisted, Denmark

Kraftvarmeværk Thisted, a waste-incineration CHP plant in Thisted, conducted a pilot project in the summer of 2021 in which 1% of the flue gases was directed into an amine scrubber for CDR based on technology originally developed for upgrading biogas. Nearly all the carbon dioxide in the flue gas directed into the scrubber was removed during the test period. The project, which pioneered waste-to-energy CDR in Denmark, was a cooperation between Thisted Kraftvarmeværk, Ammongas A/S (which provided the scrubber), and SEG A/S. The project demonstrated that it is technically possible to remove close to 100% of the carbon dioxide in flue gases. The project was awarded the Danish district heating prize Fjernvarmeprisen in 2021.

Link:
https://fjernvarmen.danskfjernvarme.dk/p/magasinet-fjernvarmen/2021-12-02/r/9/16-17/3045/473343

6.2.2 2021: Amager Bakke, ARC, Copenhagen, Denmark

Amager Bakke, a waste-to-energy CHP plant in Copenhagen owned by ARC, installed a pilot CDR unit in 2021 capable of capturing 850 kg of carbon dioxide per day. The partners in the pilot project were ARC, DTU, Pentair, and Rambøll. The pilot installation used the MEA process with extensive heat recovery. The aim was to reach net-zero energy consumption for the capturing process, using heat pumps and district heating to reuse even the low-grade excess heat from the process. In 2023, the pilot installation was replaced by a demonstration plant capable of capturing 4 tonnes of carbon dioxide per day.

ARC failed to get a grant from the EU Innovation Fund in 2022. This is expected to delay the project's full-scale implementation, which was originally planned for 2025 and can capture 500,000 tonnes of carbon dioxide yearly.

Links:
https://online.flippingbook.com/view/596430928/4/

https://a-r-c.dk/english/demonstration-plant-for-carbon-capture-2023/
https://ramboll.com/projects/rdk/arc-amager-bakke-carbon-capture,
https://danskfjernvarme.dk/aktuelt/nyheder/2023/nyt-anlaeg-markerer-start-paa-potentielt-co2-eventyr

6.2.3 2022: Filbornaverket, Öresundskraft AB, Helsingborg, Sweden

Filbornaverket, a waste-to-energy CHP plant in Helsingborg owned by Öresundskraft AB, conducted a four-month test period in 2022 to evaluate a small HPC-process installation for CDR (Bioenergi, 2022). This constitutes Sweden's first test of the HPC process in a waste incineration CHP plant. One objective of the study was to investigate the total energy consumption of the process with heat recovery, with the aim to reach 1 MJ/kg carbon dioxide (Energimyndigheten, 2022).

Additionally, an amine-based CDR process was investigated in a previous evaluation. At the time of writing, it has not yet been decided which technology will be proposed for a future full-scale installation. Following the final investment decision planned for 2025 (Bioenergi, 2023b), a full-scale implementation could be launched in 2027; this is then projected to remove 210,000 tonnes of carbon dioxide yearly, of which 120,000 tonnes would be of biogenic origin.

6.2.4 Planned: Klemetsrud CHP plant, Oslo, Norway

The CHP plant Klemetsrud in Oslo, which is owned by Hafslund Oslo Celsio, is building the world's first full-scale CDR facility with storage for waste incineration. The facility is expected to be in operation in 2026 (Valestrand, 2023). The Norwegian government is supporting the development with NOK 3 billion; the Oslo municipality is providing NOK 2 billion. The municipality's support is motivated by the large climate impacts of the CHP plant, which currently accounts for 17% of the carbon dioxide emissions in Oslo. The total project investment is estimated to be NOK 9.1 billion for a CDR capacity of 400,000 tonnes. An amine-based process will be used, and it is reported that heat recovery to the district heating network is key for the economic viability of the facility.

Link:
https://www.projectaccsess.eu/partners/hafslund-oslo-celsio/

6.2.5 Proposed: Vestforbrænding, Glostrup, Denmark

Vestforbrænding, a Danish waste management and energy company, competed for the first contract in the Danish state aid programme for CDR in spring 2023. Even though they did not win the contract, they intend to pursue the CDR development, albeit with a slightly longer time frame. They have proposed an onshore alternative for storing carbon dioxide, which they claim is a simpler than an offshore solution.

Link:
https://danskfjernvarme.dk/aktuelt/nyheder/2023/co2-fangst-vestforbraending-er-stadig-klar-til-at-gaa-i-gang?link_id=49998ed8-7376-4120-9bf2-c829de8d04a0

6.3 PLASTIC RECYCLING BEFORE INCINERATION

To reduce the share of plastics that are incinerated in favour of recycling, several measures can be adopted. One is to increase the number of plastic types that can be recycled; another is to separate plastics from household waste; a third is to use chemical recycling on complex plastics that are not easily recycled mechanically.

6.3.1 2021: Stockholm Exergy and SÖRAB, Märsta, Sweden

Stockholm Exergi AB, in cooperation with SÖRAB, has installed Sweden's first post-sorting facility for plastics in household waste. The facility, which began operations in 2021 (Wickström, 2021), was added to the Brista 2 waste incineration CHP plant. With a capacity of sorting out 18,000 tonnes of plastics (and 2,500 tonnes of metals), the facility can reduce carbon dioxide emissions by 36,000 tonnes annually. The sorted plastics are sent to Svensk Plaståtervinning's facility Site Zero, which is described in the next case below (6.3.2).

6.3.2 2023: Svensk Plaståtervinning, Motala, Sweden

Svensk Plaståtervinning AB has built the world's largest recycling facility for plastics in Motala, Sweden. The facility, named Site Zero, will be commissioned in two phases: phase one is planned to be finalised in 2023, and phase two in 2025. Phase one brings a capacity to handle 200,000 tonnes of plastics yearly and sort 12 different types of plastics. This means that close to all plastics used in packaging in Sweden may be sorted and recycled. The small fraction of plastics that may not be recycled will be incinerated with carbon capture and storage (CCS). Phase two includes washing and granulation of the plastics (mechanical recycling), which is a major step towards achieving a circular plastic flow in Sweden. The SEK 1 billion project has received SEK 180 million in funding from the Swedish Environmental Protection Agency (Klimatklivet).

In 2022, Svensk Plaståtervinning announced an investment in a new line that facilitates the sorting of plastics removed from household waste at post-sorting facilities. These plastics, which would otherwise have been incinerated, are heavily contaminated and need special treatment, which can be provided by the new line. This second investment has received a SEK 108 million grant from Klimatklivet.

Links:
https://www.svenskplastatervinning.se/site-zero/
https://www.svenskplastatervinning.se/miljonstod-mojliggor-atervinning-av-komplex-plast-fran-landets-eftersorteringsanlaggningar/

6.3.3 Proposed: Borealis, Stenungsund, Sweden

The chemicals company Borealis in Stenungsund, Sweden, a major producer of plastics raw materials, has announced a feasibility study on the chemical recycling of plastics. The project, partnered by Stena Recycling, received funding from the Swedish Energy Agency (Energimyndigheten). Given the positive study outcomes, operations are expected to begin in 2024 or 2025. A cooperation has also been announced between Borealis and Svensk Plaståtervinning about using this facility to process complex plastics from Site Zero (case 6.3.2) that cannot be recycled mechanically.

Links:
https://www.borealisgroup.com/news/true-to-its-everminds-mind-set-borealis-drives-collaborative-project-in-sweden-to-increase-supply-of-chemically-recycled-feedstock-for-the-manufacture-of-more-circular-base-chemicals-and-plastic-products
https://www.svenskplastatervinning.se/unik-cirkular-kemisk-atervinning-nytt-samarbete-mellan-svensk-plastatervinning-och-borealis/

6.3.4 Proposed: Neste/Alterra energy, Porvoo, Finland

Neste, a chemicals company headquartered in Finland, announced in 2022 the purchase of the European rights to Alterra Energy's thermochemical liquefaction technology for the chemical recycling of plastics. The company plans to introduce the technology in their Porvoo refinery in Finland.

Link:
https://www.neste.com/releases-and-news/circular-economy/chemical-recycling-plastic-neste-acquires-european-rights-alterra-energys-thermochemical

6.3.5 Proposed: Fossil Eye, Linköping, Sweden

Tekniska Verken, a regional energy company in Linköping, is developing a pilot facility called the Fossil Eye for measuring the amount of fossil plastics in household waste at the customer level. The effort is a cooperation between Tekniska Verken, Vattenfall, and Umeå Energi. The aim is to reduce the plastics in household waste by introducing a separate fee for the fossil share of the waste. This approach gives customers direct feedback about their waste, thereby incentivising better segregation of plastics at the household level.

Link:
https://www.tekniskaverken.se/om-oss/innovation/fossileye/?nav=visible
https://energiforsk.se/nyhetsarkiv/det-fossila-ogat-okar-atervinningen-av-plast/

6.4 SUMMARY CONCERNING REMOVING CARBON DIOXIDE

There are many ongoing projects related to district heating in the Nordic countries where carbon dioxide removal (CDR) from flue gases is on track for implementation. CHP plants fuelled by biomass or waste are the typical contexts for these initiatives. While the technology for CDR exists, key success factors are likely to include high energy efficiency and heat recovery, which are the focus of many projects. A complementary method to remove carbon dioxide is to redirect fossil plastics in waste streams to recycling.

If the carbon dioxide is permanently stored, as planned in most projects, carbon dioxide emissions are reduced. If the fuel is of biological origin, such as biomass, negative carbon dioxide emissions can be achieved if there is a corresponding sustainable regrowth of the biomass.

Due to the urgency of decarbonisation, a remuneration scheme for CDR should be considered to increase the incentive for district heating companies to use the CDR methods presented in this chapter to reduce carbon dioxide emissions.

7 Supplying heat: Linear renewable supply

The heat supply possibilities presented in this report are categorised over three chapters (7-9). This chapter deals with the linear heat supply possibilities based on renewables. That is base load possibilities without any heat recycling. The next two chapters cover heat recycling and supplying heat to meet peak demand.

The nine possibilities of renewable heat supplies in linear heat supply are divided into four different main groups of possibilities: **geothermal, solar, electrical,** and **ambient heat.** The geothermal heat possibilities are split into five categories: **volcanic zones, hydrothermal aquifers, crystalline bedrocks, abandoned mines, and shallow grounds**. These five categories reflect the widely different exploration contexts of geothermal heat.

The current situation and future prospects of geothermal heat globally are summarised in (Lund and Toth, 2021) and (Lund et al., 2022), while the European situation is summarised in (Sigfússon and Uihlein, 2015), (Bielewski et al., 2022), and (EGEC, 2023).

Geothermal sources can be classified into deep or shallow sources based on the depth needed to attain the required temperature. Deep geothermal refers to depths ranging from several hundred metres to some kilometres. Shallow geothermal refers to borehole depths of down to a few hundred metres.

Harnessing geothermal energy for district heating can be through closed or open loops. In closed-loop systems, the underground water does not move, and the heat is exchanged via a vertical or horizontal water loop. In open-loop systems, the water flows from the warm host underground reservoir to either the environment or another colder underground well.

The sixth possibility is using large solar collector fields in solar district heating systems, while the seventh possibility is using large electric boilers to utilise excess electricity during windy days. The eighth possibility is using large heat pumps with low-temperature ambient heat from sea and lake waters. The ninth possibility is using large heat pumps with low-temperature ambient heat from air.

The locations if the identified cases concerning linear renewable supply are shown in Figure 19.

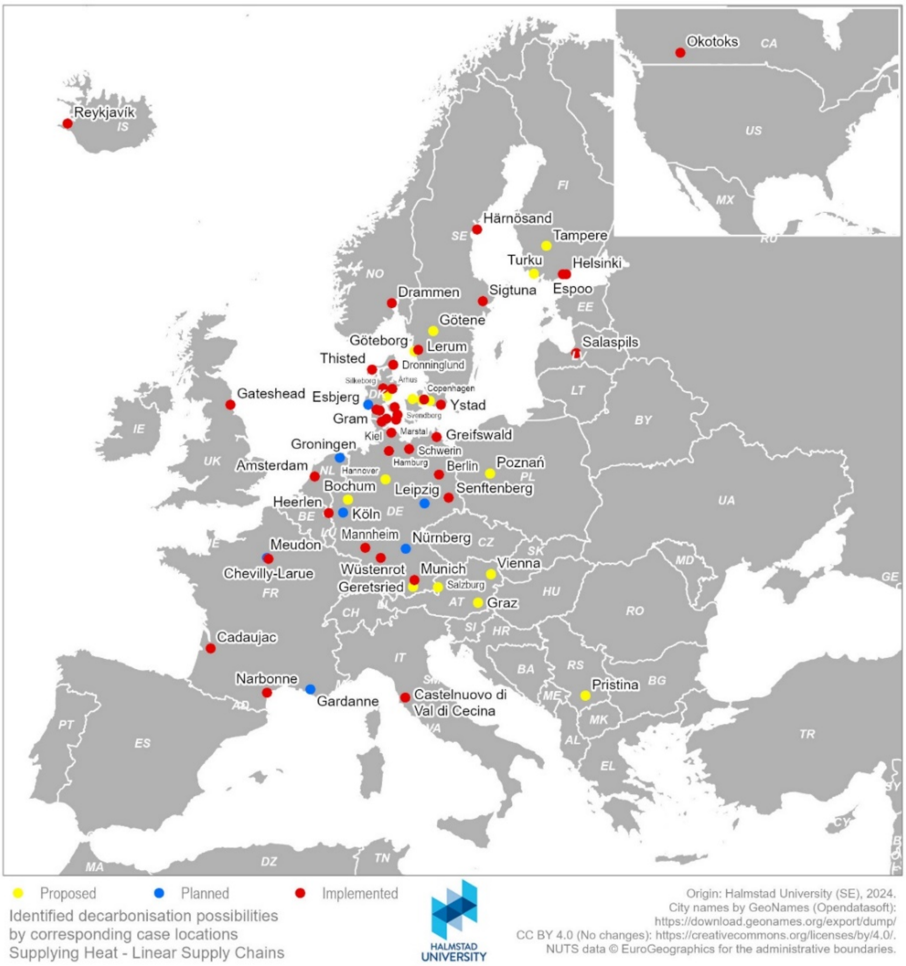

Figure 19. Map showing the locations of cases in the database concerning supplying heat by linear renewable supply.

7.1 GEOTHERMAL HEAT FROM VOLCANIC ZONES

Hot groundwater from volcanic zones can be exploited for heat generation purposes, where direct heating is the most straightforward application. The mass flow rate and the geothermal source's temperature determine the geothermal fluid's potential in district heating applications.

Geothermal energy is commonly harvested worldwide in areas with young volcanoes. Iceland and Tuscany in Italy are the two only areas in Europe where geothermal heat is extracted from volcanic zones for district heating systems.

Geothermal energy from volcanoes is reliable since, unlike many other renewable energy sources like wind or solar, it is not subject to fluctuations. Another advantage of volcanic geothermal energy is its high capacity. One of the most significant drawbacks is that geothermal projects have high initial costs. Both drilling deep enough into the Earth's crust to reach the necessary heat and installing geothermal systems are costly processes.

Reference: (Dincer and Ozcan, 2018)

7.1.1 1930: Reykjavik, Iceland

Iceland stands out as one of the most geologically active areas globally, characterised by a significant volcanic presence. With a staggering count of over 200 volcanoes, Iceland experiences an average of 20 to 30 volcanic eruptions per century. The country boasts more than 25 high-temperature regions within its volcanic zones, where temperatures can soar up to 200°C at depths beyond 1,000 metres. Additionally, around 250 low-temperature regions with temperatures not exceeding 150°C have been identified. Moreover, there are more than 600 hot spring fields with temperatures over 20°C. This geographic condition has provided an excellent opportunity for Iceland to harvest geothermal heat.

Currently, almost 62% of the primary energy supply in Iceland comes from geothermal sources. Geothermal resources are utilised for both electricity generation and direct uses. In high-temperature (>200°C) fields, eight CHP sites generate electricity and heat. The low-temperature (<150°C) areas are exploited mainly to supply hot water for district heating. Direct uses of geothermal energy for heating are estimated to total 9.3 TWh of heat annually. The largest geothermal application is space heating, with a share of 45%, followed by electricity generation at 39%.

Approximately 30 geothermal district heating systems operate in Iceland's towns and villages. In addition, around 200 small systems exist in rural areas. Reykjavík Energy is by far the largest geothermal district heating utility in Iceland, providing heat for the capital Reykjavík and its neighbouring towns. It serves about 240 000 people, corresponding to 65% of the entire population in Iceland. Nevertheless, the geothermal potential is far beyond what is currently being exploited. On the other hand, increased environmental awareness has led to a consensus on protecting natural areas, leading to opposition to hydropower and some geothermal projects.

Reference: (Ragnarsson et al., 2020)

7.1.2 1955: Larderello, Italy

Located in central Italy, the Larderello geothermal power complex is one of the world's oldest geothermal plants. The first unit was commissioned more than a century ago, in 1913. The complex now comprises 34 plants with a total capacity of around 900 MW of electricity generation. Reservoir depths at the geothermal field range from 700 to 4 000 meters below the surface.

The geothermal heat from these plants is also used for local district heating systems. The first was commissioned in 1955; currently 21 geothermal systems are in operation in municipalities located in the vicinity of Larderello.

Reference: (AIRU, 2021)

Links:
https://www.power-technology.com/features/oldest-geothermal-plant-larderello
https://www.geoenergyservice.it/impianto/
http://geodh.eu/wp-content/uploads/2015/01/IT_Pomarance_GeoDH.pdf

7.2 GEOTHERMAL HEAT FROM AQUIFERS

Geothermal aquifers are permeable layers of fluid-bearing bedrocks. Part of the heat that flows from the Earths interior to its surface is stored in aquifers and can be used directly for heating and cooling. When subsurface temperatures are sufficiently high, the heat can also be used to generate electricity.

To tap into geothermal energy, it is often necessary to drill wells that can be several kilometres deep, depending on the location of the geothermal aquifer. In certain cases, temperatures as high as 80°C can be reached. Hot geothermal water is pumped up to the surface through the boreholes, and its thermal energy is captured via heat exchangers. The heat is then transferred to the water in the district heating network in a closed circuit, while the geothermal water is pumped back into the underground reservoir. Depending on the water temperature from the underground, a large heat pump may be necessary to raise the temperature to the level needed in the district heating network.

Geothermal energy holds significant energy potential, yet its effective utilisation relies on several factors. The feasibility of exploiting this potential is contingent upon favourable underground conditions, such as adequate flow and temperature of geothermal resources. Additionally, the availability of suitable areas in proximity to the district heating network plays a crucial role. This aquifer possibility is the most frequent in Europe for geothermal heat supply into district heating systems.

References: (Limberger et al., 2018), (Garabetian et al., 2021)

Link:
https://www.nordeafunds.com/da/artikler/dansk-selskab-vil-revolutionere-nordeuropas-fjernvarme

7.2.1 1985: SEMHACH, Chevilly-Larue, France

The SEMHACH company manages the geothermal heating system that supplies three suburban towns south of Paris (L'Haÿ-les-Roses, Chevilly-Larue, and Villejuif). Previously, the network was supplied by two geothermal plants. Each unit comprised two wells, one for pumping hot water and one for reinjecting it in the same layer, at least one kilometre away, to not cool the hot water source. The re-injection is mandatory to preserve the resource since the water is very salty and cannot be injected near the surface for environmental reasons. The company also built a third plant, which was put into operation in 2017 and supplied heat to nearly 40 000 households by 2020, saving more than 36 000 tonnes of carbon dioxide annually.

The network configuration used in this network is presented in case 4.3.1.

References: (Faessler, 2015, Faessler, 2016, Faessler and Lachal, 2017)

Link:
https://www.semhach.fr/
https://www.thinkgeoenergy.com/new-geothermal-heating-development-under-way-in-paris-france

7.2.2 2004: Stadtwerke München, Munich, Germany

Munich is located in the south of Germany, north of the Alps. The region around Munich currently contains about 30 geothermal wells for both electricity and heat generation, since it is situated above the Molasse Basin (also known as the Malm), which contains large amount of warm geothermal water.

In 2008, Stadtwerke München (SWM) established a long-term vision with three pillars: (1) all electricity supply should be renewable by 2025, (2) the district heating system should be carbon dioxide neutral by 2040, and (3) district cooling should be able to substitute individual air conditioning units. The vision was refined in 2012: geothermal heat should be the main tool for reaching the district heating vision (Stadtwerke München, 2012) and (Frey and Miller, 2017). The backbone of the current heat supply is traditional CHP plants using fossil fuels. The current annual heat sales exceed 4 TWh and the heat is distributed by a trench length of 900 km. These heat deliveries cover about one third of the current heat demand in Munich.

The strategy for reaching the long term district heating vision has included cooperation with geothermal professionals, participation in research projects such as the GRAME project with the Technical University of Munich and the early LowEx project (Henke et al., 2015), and one step-by-step introduction of geothermal plants. The early days of this transformation process are summarised in (Farquharsson et al., 2016).

SWM currently operates six geothermal plants, where some of them also generate electricity via ORC. The first geothermal plant was commissioned in 2004 in Riem, in the eastern part of Munich. The Sauerlach CHP plant, located south of Munich, went into operation in 2014. The third plant was Freiham, located in the western part of Munich, which was commissioned in 2016. In 2016-2017, two private geothermal power plants in Dürrnbar and Kirchstockach were purchased with the intention to also exploit them for heat supply. The Sendling plant located next to the central Süd CHP plant became the sixth plant in 2022. The borehole depths vary between 2500 and 5000 metres, while the temperature of the geothermal fluid varies between 90 and 140°C, where the latter temperatures are found in the south of Munich.

The seventh geothermal station is planned for the Michaelibad district: drilling will start in 2024 and commissioning is expected in 2029. The current plan is to have a total heat capacity by 400 MW in 2040 together with an electrical capacity of 50 MW from all geothermal sources.

Links:
https://www.swm.de/energiewende/waermewende
https://www.swm.de/dam/doc/english/swm-sustainability-report.pdf
https://www.swm.de/dam/doc/english/swm-annual-report.pdf

7.2.3 2007: Sønderborg Fjernvarme, Sønderborg, Denmark

In 2007, DONG Energy (now Ørsted) and the consumer-owned district heating company Sønderborg Fjernvarme joined forces to assess the feasibility of harnessing geothermal energy from the underground in Sønderborg, Denmark. The primary objective of this collaboration was to explore the potential of utilising geothermal energy as a heat source for the local water-based district heating system.

Following the seismic surveys, two wells (one for production and one for injection) with a depth of 1200 metres were drilled in 2010. The production temperature reached 48°C, while the injection temperature was 15°C. Geothermal fluid flowed at a rate of up to 335 m^3/h, and the distance between boreholes ranged from 840 to 1 200 metres. The geothermal capacity was 12 MW, or 29 MW including the driving heat for the absorption heat pump. One challenge of the project was that the primary target reservoir was not found. However, the secondary option was better than expected. Because of problems in the plant's injection well, the facility has not contributed to heat generation since 2018.

Sønderborg Fjernvarme and Innargi reached an agreement in early 2023 to try to restart the extraction of geothermal heat in this location. However, this potential restart was rejected by the district heating company in January 2024, when they communicated that this geothermal project is too expensive compared to alternative options.

Links:
https://www.sonderborg-varme.dk/om-os/produktionsanlaeg/vores-produktionsanlaeg
https://danskfjernvarme.dk/aktuelt/nyheder/2023/soenderborg-varme-vil-genoplive-geotermi
https://www.sonderborg-varme.dk/om-os/om-soenderborg-varme/nyhedsarkiv/pressemeddelelse-soenderborg-varme-nedlaegger-geotermianlaeg/

7.2.4 Planned: GeoMeudon, Meudon, France

The French municipality of Meudon and Engie Solutions have created GeoMeudon, the company that will build and operate a planned geothermal plant in Meudon. The aim of exploiting geothermal energy is to reduce fossil fuel consumption and prevent heat prices from energy soaring. The plan is to supply heat for 15 000 residents by 2026. This corresponds to 83% of the total heating needs of the district. The investment needed for this transition was estimated to be 37 million euro. The use of geothermal energy, together with a heat pump, will prevent 17 700 tonnes of carbon dioxide emission annually. In addition, heat bills are expected to decrease by 25% - 40%. The transition was scheduled to begin in 2023 by dismantling the existing gas boiler. At the same time, the drilling of geothermal boreholes and the construction of a new auxiliary gas boiler room was begun.

Link:
https://www.thinkgeoenergy.com/meudon-france-targets-geothermal-district-heating-by-2026

7.2.5 Proposed: Innargi and Kredsløb, Aarhus, Denmark

The geothermal company Innargi and the Kredsløb utility company intend to bring into operation the EU's largest geothermal district heating plant in the Danish city of Aarhus. The proposed scheme is a 110 MW geothermal plant to supply heat to Aarhus starting in 2025. The plant will reach full capacity by 2030, covering approximately 20% of the district heating demand. The project aligns with the goal of phasing out imported wood pellets by 2030.

By using geothermal heat through this project, it would be possible to reduce the amount of imported wood pellets, which is currently 55 000 tonnes per annum. Consequently, 95 000 tonnes of biogenic carbon dioxide emissions would be avoided. If the saved biomass is used to produce methanol for transport, an additional 70 000 tonnes of carbon dioxide emissions could be saved. Innargi bears the risk in all project phases, including underground-related operational problems and reaching a lower underground temperature than expected.

Links:
https://www.kredslob.dk/om-os/presse-og-medier/pressemeddelelser/2022-pressemeddelelser/140122-presse-eus-stoerste-geotermiske-fjernvarmeanlaeg-bygges-i-aarhus
https://danskfjernvarme.dk/aktuelt/nyheder/2023/det-var-en-tilfaeldighed-der-fik-geotermi-til-aarhus
https://danskfjernvarme.dk/aktuelt/nyheder/2023/en-milepael-for-geotermien-borearbejdet-er-i-gang-i-aarhus
https://danskfjernvarme.dk/aktuelt/nyheder/2023/saadan-borer-man-17-geotermibroende-i-aarhus
https://innargi.com/third-geothermal-drilling-commences-in-aarhus/

7.2.6 Proposed: Innargi and HOFOR, Copenhagen, Denmark

The heating companies in the Danish capital of Copenhagen and Innargi reached an agreement in late 2022 to explore the possible use of geothermal energy. Innargi’s main task is to extract hot water from the underground. The role of companies VEKS, CTR, and HOFOR is to purchase thermal energy and deliver it to customers through the district heating network. The energy potential of the proposed plan is anticipated to correspond to the demand of 35 000-75 000 households. The preparation of a detailed plan, including the possible locations of the facilities and the project’s schedule, is expected to take one year. If the agreement is finalised and everything goes as expected, the first geothermal plant of a series will be ready to provide heat for the city’s district heating system in 2026. The ultimate goal is to have a 100% green district heating system.

Link:
https://www.hofor.dk/pressemeddelse/rammeaftale-laegger-sporene-for-geotermi-i-hovedstadsomraadet

7.2.7 Proposed: Innargi and Skanderborg-Hørning Fjernvarme, Skanderborg, Denmark

As the first consumer-owned district heating company, Skanderborg-Hørning Fjernvarme has an agreement with the geothermal company Innargi to investigate the possibility of harnessing geothermal energy for district heating. The purpose of the proposed scheme is to supply heat to two Danish towns, Skanderborg and Hørning. Their district heating systems are already green as they use locally produced biomass as fuel. The ambition is to make it more sustainable by replacing a large part of the biomass in the future. The introduction of geothermal energy is a promising sustainable option that will make the company less susceptible to changes in biomass prices, resulting in lower heat prices for customers. The district heating company has begun work on the master plan, which was planned to be finalized in 2023. The most crucial prerequisite before going through the operational phase is to connect the grids in Hørning and Skanderborg so that a sufficient basis for geothermal heat is ensured.

Link:
https://www.danskfjernvarme.dk/aktuelt/nyheder/arkiv/2022/221115-skanderborg-h%c3%b8rning-fjernvarme-siger-ja-til-geotermi

7.2.8 Proposed: Innargi and Fors, Holbæk, Denmark

The supply company Fors and the company Innargi are evaluating the potential application of geothermal energy to supply heat for district heating in the Danish town of Holbæk. At present, the city's residential sector is almost entirely reliant on natural gas for heating purposes, making it the largest gas-heated city in Denmark. Fors's task is to transition the city away from natural gas. The two main concerns regarding this green transition are developing a district heating network and finding the best portfolio of energy sources to provide heat. Holbæk is building a new and modern district heating system that will work efficiently at approximately 80°C. The geothermal water temperature is expected to be in the range of 60-80 °C. This would be an energy-efficient match as little electricity would be required by the heat pumps to increase the geothermal water temperature to the district heating operational level. Innargi believes geothermal heat can be extracted in Holbæk in support of district heating expansion. The preliminary assessment found that the city needs one or two pairs of geothermal wells with a supply capacity of 15-30 MW.

In October 2023, Fors announced that the geothermal option was not viable in the current situation.

Links:
https://www.fors.dk/fors-a-s-og-innargi-indgaar-rammeaftale-om-geotermi-til-holbaek
https://www.fors.dk/geotermi-som-opvarmningsform-i-holbaek-udskydes/

7.2.9 Proposed: Innargi and Veolia Poznan, Poznan, Poland

Innargi has signed a letter of intent with the local utility Veolia to investigate the potential of geothermal energy for district heating in Poznan, Poland's fifth largest city. The proposal, if realised, would be the first project of Innargi outside Denmark. The aim is to examine the possibility of installing a 100 MW geothermal plant, which would demonstrate the utilization of geothermal energy for large district heating systems. The feasibility and assessment studies began in 2023. If the studies support the use of geothermal heat, the full operation is expected to be realised in five years. The project aligns with the ongoing local efforts to substitute coal, decarbonise district heating, improve air quality, enhance energy efficiency, diversify renewable energy sources, and stabilise district heating prices for the end users. Innargi assumes the responsibility for the investment costs and risks during the exploration, construction, and operational phases.

Link:
https://www.thinkgeoenergy.com/innargi-to-explore-geothermal-potential-in-poznan-poland

7.2.10 Proposed: Innargi and Kiel Stadtwerke, Kiel, Germany

Innargi has an agreement with the local utility Stadtwerke Kiel to explore the subsurface of the German city of Kiel to assess the local potential of geothermal energy for district heating use. The proposed plan aims to further decarbonise the city's district heating system in line with the target of achievingclimate neutrality in the district heating supply by 2035. The initial investigation was planned to be completed by the end of 2023. The extension of the agreement on the construction and operation of geothermal heating power plants depends on the assessment's outcome. Estimates show that to reach geothermal waters with a temperature of 76°C, boreholes with a depth of 2-3 km are needed. The geothermal water needs to be further heated by large heat pumps since the existing district heating system works at 90°C. Once the geothermal heat is extracted, the cycle is closed by pumping the cooled water underground via an injection well.

Links:
https://innargi.com/stadtwerke-kiel-and-innargi-investigate-the-potential-for-geothermal-district-heating/
https://www.thinkgeoenergy.com/innargi-to-explore-geothermal-district-heating-in-kiel-germany

7.2.11 Proposed: Wien Energie, Vienna, Austria

Wien Energie and the fossil-based OMV company have joined forces to provide geothermal heat for the district heating system in Vienna. The ambition with the joint venture is to combine OMW's experience from oil exploration with the district heating experience of Wien Energie. The two partners have already explored and proved the geothermal potential of the eastern Vienna Basin as part of the GeoTief Wien research project.

The drilling for the first plant will start at the end of 2024 and the expectation is to supply geothermal heat in 2027. The plant will generate about 20 MW of heat in combination with heat pumps.

Links:
https://www.geotiefwien.at/

https://www.wienenergie.at/tiefengeothermie-aspern/
https://www.wienenergie.at/pressrelease/wien-energie-und-omv-kooperieren-bei-der-entwicklung-der-tiefengeothermie-im-grossraum-wien/
https://www.wienenergie.at/pressrelease/fuer-klimaneutrale-fernwaerme-wien-energie-und-omv-gruenden-joint-venture-fuer-tiefengeothermie/
https://waste-management-world.com/waste-to-energy/climate-neutral-district-heating-wien-energie-and-omv-establish-joint-venture-for-deep-geothermal-energy/

7.2.12 Proposed: ENEX, Geretsried, Germany

An important condition when utilising an aquifer heat source is that the two boreholes should interact under-ground to facilitate heat transportation. Several exploration projects have been rejected for not having a suitable hydraulic connection between the source and sink boreholes. This was the case in Geretsried, Germany where ENEX received an exploration license for geothermal heat in 2004.

To overcome the lack of a connection between the two boreholes in Geretsried, a closed-loop solution will be explored for getting a viable geothermal source. The Eavor-Loop technology is a novel geothermal solution where a closed loop system is drilled at a deep level. It was invented by the Eavor Technologies company from Calgary, Canada, which has a background in oil and gas exploration. The technology has been developed and verified through an installation in Canada.

The drilling in Geretsried started in October 2022 and there are four closed loops planned. The first loop will be completed in summer 2024 and all four loops are planned to be completed by autumn 2026. Each closed loop requires 89 km of drilling, comprising two vertical boreholes 4.5 km and 12 pairs of horizontal boreholes, each 3.5 km long. The temperature at 4.5 km is about 160°C and the expected temperature from the loop is 120°C. The different water density in the loop due to temperature differences creates a natural circulation eliminating the need for pumps. Each loop will generate 16 MW of heat and 2 MW of electricity. In total, the four loops will provide 64 MW of heat and 8 MW of electricity.

This project has received a grant from the EU Innovation Fund in the 2021 call, as discussed in Sub-section 10.6.5.

Links:
https://www.eralberta.ca/uncategorized/first-of-its-kind-geothermal-pilot-project-underway-in-alberta/
https://www.thinkgeoenergy.com/eavor-technologies-commences-construction-of-geothermal-demonstration-facility/
https://www.eavor.com/press-releases/eavor-announces-a-commercial-eavor-loop-project-to-be-built-in-geretsried-germany/
https://renewablesnow.com/news/eavor-enex-to-co-develop-geothermal-heat-and-power-project-in-germany-697444/
https://www.thinkgeoenergy.com/eavor-and-enex-break-ground-on-geothermal-project-in-geretsried-germany/
https://www.eavor.com/technology/
https://eavor-geretsried.de/en/

https://www.eavor.com/press-releases/eavors-next-generation-geothermal-project-awarded-916-million-grant-from-the-european-innovation-fund/
https://www.eavor.com/press-releases/eavor-commences-commercialization-through-major-investment-and-landmark-partnership-with-omv/

7.2.13 Proposed: Enercity, Hannover, Germany

The Eavor-Loop technology described in the previous case has also been selected for a geothermal project in Hannover. According to an initial agreement between Eavor Technologies and Enercity, the geothermal boreholes are expected to deliver 30 MW in 2026, providing an annual heat output of 250 GWh.

Reference: (Enercity, 2023)

Links:
https://www.enercity.de/presse/pressemitteilungen/2023/co2-freie-tiefengeothermie-in-hannover-enercity-und-eavor-schliessen-waermeliefervertrag
https://www.energie.de/euroheatpower/news-detailansicht/nsctrl/detail/News/enercity-und-eavor-schliessen-waermeliefervertrag-zu-geothermieprojekt-in-hannover

7.3 GEOTHERMAL HEAT FROM CRYSTALLINE BEDROCKS

Crystalline bedrocks dominate the underground in Finland and Sweden, resulting in completely different conditions for the utilisation of deep geothermal heat compared to other parts of Europe, which have a rather high availability of aquifer geothermal sources in sedimentary bedrocks. According to the reference below, no geothermal heat is utilised from crystalline bedrocks in European district heating systems. However, three expensive demonstration plants for electricity generation have been implemented or are expected to be implemented, mainly financed by research grants. These plants are located in France (Soultz-sous-Forêts and Rittershoffen) and in the United Kingdom (Redruth, Cornwall).

The seven cases from Finland and Sweden presented below tried to advance the current knowledge of geothermal exploration in crystalline bedrocks.

Reference: (Sjöqvist and Tillberg, 2023)

7.3.1 2023: Qheat, Espoo, Finland

In early 2023, the Finnish geothermal heat company QHeat completed the heat supply connection from three initial geothermal wells in the Finnoo project. Finnoo is a new sustainable residential maritime area being built in the city of Espoo to provide housing for 17 000 residents in the 2030s. The heat will be transferred through Finland's first geothermal low-temperature district heating network, which is being built by QHeat in cooperation with two other companies. The initial deep geothermal wells, with a 1500 metres depth, deliver heat to six buildings comprising 250 flats. The heat extracted from the boreholes has a temperature of almost 30°C and 1900 MWh of heat per year will be supplied into the local network after the additional heat pumps.

It is estimated that the completion and commissioning of the geothermal plant will reduce the amount of energy purchased by the six buildings by 25% and the corresponding carbon dioxide emissions from heating by 90%. QHeat has developed a novel well design that use a coaxial flow to harness geothermal energy from medium-depth thermal reservoirs. This novel method is employed in the Finnoo project. The technique includes storing geothermal heat in the soil and extracting the heat from it. An insulated pipe makes it possible to change the direction of the coaxial flow depending on the required use so that the entire length of the well can be exploited for efficient heating and cooling.

An important feature of most deep geothermal cases is that rather high temperatures can be extracted from the underground. This is not the situation in this deep case since heat pumps are required to upgrade the low-temperature geothermal heat to meet the higher demand temperatures. Thus, this case uses the same configuration as used for shallow geothermal cases based on ground-source heat pumps (as presented in section 7.5).

Link:
https://www.thinkgeoenergy.com/finland-one-step-closer-to-having-first-geothermal-district-heating-network
https://www.qheat.fi/in-geothermal-energy-size-matters/
https://www.qheat.fi/portfolio/peijinkatu-8-finlands-first-low-temperature-geothermal-heating-network/

7.3.2 Planned: Tampereen Sähkölaitos, Tampere, Finland

Tampereen Sähkölaitos is leading a project to evaluate the possibility of extracting heat from deep geothermal wells in Tarastenjärvi, a district in the Finnish city of Tampere. This pilot project aims to test the hydraulic shock technique to drill a 3 km well near a waste-to-energy power plant. The drilling began in late 2021. The project follows the single-well principle in whereby the geothermal water is circulated in a closed loop by using two screen sections in the well. The deeper screen section facilitates the pumping of the groundwater, while the shallower screen section helps return the water to the aquifer.

A consortium of 15 energy companies from different Finnish cities has been formed to implement the project. If the drilling pilot goes well and the anticipated thermal energy is accessible, the project discussion will be expanded to deeper wells. Based on the preliminary estimates, significant heat is available to be used as a source of district heating at a depth of about 7 km.

Link:
https://www.oulunenergia.fi/en/news/062021/oulun-energia-explores-the-potential-of-geothermal-heat

7.3.3 Planned: Helen, Helsinki, Finland

The Helen company plans to build a medium-depth geothermal plant in the district in Ruskeasuo, Helsinki. The geothermal plant will serve as Helen's pilot site, for testing and developing drilling technology and other technical solutions for geothermal sites. The annual district heating and cooling generation of this pilot plant will be 1.8 GWh and 0.8 GWh, respectively. The depth will be approximately 2.5 km, where the ground temperature is around 40°C. The drilling is estimated to take four months. The advantages of 3D seismic reflection surveying and artificial intelligence are also being evaluated. The experience gained will be applied to future geothermal projects that involve deeper drilling in the range of 4-7 km.

Link:
https://www.helen.fi/sv/uutiset/2021/byggstart-for-geovarmeanlaggningen-i-brunakarr-i-helsingfors

7.3.4 Proposed: St1, Espoo, Finland

The fossil company St1 started the world's deepest industrial geothermal energy project in the Finnish city of Espoo in 2014. The aim was to investigate the techno-economic feasibility of harnessing geothermal energy in the crystalline rock conditions of Finland for district heating applications. An enhanced geothermal system (EGS) was to be built at a depth of 5-6 km. The first well was drilled to the final depth of 6.4 km in 2018. Due to the low geothermal gradient in the study area (15-17°C/km), such extreme depths were necessary to reach a temperature above 100°C, which is required by the local district heating utility Fortum. Two wells over 6 km deep were drilled where the bedrock temperature is about 120°C.

In early 2023, it became clear that the project had to be stopped. The reason was that water could not flow sufficiently from one well to another. Furthermore, the capacity output of the planned heating plant would not have been high enough to be commercial. The site is now available for scientific research. The wells provide a research environment for geothermal energy, geosciences, and even microbiology studies. The gained knowledge in geophysics and geology forms a solid basis for St1's upcoming projects.

Reference: (Kukkonen and Pentti, 2021)

Links:
https://www.st1.com/fi/st1n-otaniemen-geotermisen-pilottiprojektin-syvat-lampokaivot-tutkimuskayttoon
https://www.energi-miljo.se/nu-ska-det-forskas-pa-de-djupa-brunnarna-i-finland/

7.3.5 Proposed: EON and St1, Malmö, Sweden

The E.ON company planned to build a pilot deep geothermal plant in Malmö, which would be one of the first European industrial scale projects to extract heat from depths of several kilometres. The expected maximum temperature was 160°C, enough to directly feed the heat into the Malmö district heating system.

In 2020, the Finnish company St1 started to drill boreholes to depths of 5-7 km. The plan was to construct five geothermal heat plants in the city by 2028, each with an installed thermal capacity of 50 MW. The geothermal heat would substitute biofuels and biogas for heat generation and support the city in realising its ambition to be emission-free by 2030.

Other partners to E.ON in this 5 million euro project included the Swedish Energy Agency, the Geological Survey of Sweden, the City of Malmö, and the University of Uppsala. According to personal communication with E.ON, this geothermal project has now been postponed.

Reference: (Juhlin et al., 2022)

Links:
https://www.eon.com/en/about-us/media/press-release/2020/2020-03-03-eon-builds-deep-heat-power-plants-in-sweden.html
https://www.energimyndigheten.se/forskning-och-innovation/projektdatabas/sokresultat/GetDocument/?id=358cb003-4144-4b00-925b-3a296ba918fc&documentName=Slutrapport_Testh%C3%A5l%20f%C3%B6r%20utveckling%20av%20EGS_49110-1.pdf.pdf

7.3.6 Proposed: Göteborg Energi, Gothenburg, Sweden

Göteborg Energi has investigated the possibility of implementing deep geothermal plants in Gothenburg by using an EGS. For this purpose, two core drillings of about 1 km each were performed in a project financed by the Swedish Energy Agency. The project analysed the suitability of the local geology for future deep geothermal plants. This pilot project has provided information about the properties of the bedrock, its cracks, and the attainable temperature. Deep-drilled wells are rare in Sweden, so this project has significantly strengthened the understanding of deep geothermal resources in the Swedish crystalline bedrock.

The main conclusion from the project is that 'under the current circumstances, there does not seem to be a reasonable prospect for EGS in Gothenburg' (quote from the summary in the second reference below). The main barrier is the low natural permeability in the crystalline bedrock.

References: (Ladefoged, 2021) and (Sjöqvist and Tillberg, 2023)

Links:
https://www.energi-miljo.se/djupaste-borrningen-nagonsin-i-goteborg/
https://sverigesradio.se/artikel/goteborg-ar-for-kallt-uppvarmning-fran-underjorden-tekniskt-omojligt
https://termoinnovation.se/projekt/provborrning-for-kunskapsinsamling-om-djupgeotermi

7.3.7 Proposed: Skara Energi, Skara, Sweden

In the Västra Götaland region, four energy companies, Götene Vatten & Värme, Skara, Skövde, and Vara Energi, have joined to explore the possibility of capturing geothermal energy to make district heating more climate smart. The geothermal potential is significant but also expensive and complicated to achieve. As the first step, the companies intend to conduct an overview study to determine whether they have the abilities and necessary conditions to continue working on a geothermal plant. This idea of exploiting geothermal energy took shape when Skara Energy started planning a new biomass boiler.

Västra Götaland does not have any advantages over other places in Sweden for exploring geothermal heat, so the drilling and other experiences gained in Västra Götaland will also be useful for projects in other regions of the country. Skara Energi has already started the preliminary theoretical analysis. The company hopes to begin test drilling in 2023 or 2024. The depth of the boreholes would be between 4-8 km. The water temperature is expected to be 90°C, and the plant is estimated to have a 15 MW capacity for electricity and heat generation.

Link:
https://www.energi.se/artiklar/2022/oktober-2022/fyra-energiforetag-i-samarbete-om-geotermisk-varme

7.4 GEOTHERMAL HEAT FROM CLOSED MINES

In active mines, inflowing mine water must be removed to maintain suitable working conditions. This is done via gravity drainage in shallow mines and pumping in deep mines. When a mine is abandoned, the groundwater can be regarded as a sustainable heat source. Flooded mines form aquifers or reservoirs, that can store considerable volumes of groundwater. A mine can also be used to store residual heat from surrounding heat sources in underground corridors, as discussed in Section 5.3. While the thermal and recharging capacity of these systems is finite, the resource depletion risk is low relative to the termination risk in heat recycling projects concerning industrial excess heat. However, the extraction and injection flows must be limited to sustainable rates to avoid the exhaustion of the aquifer's capacity.

The low temperature of mine water makes it appropriate for heating in the winter and as a heat sink for cooling in the summer. A heat pump is needed to increase the water temperature for heating purposes. It can be used as a centralised solution for a district heating network or individually by consumers. Compared to conventional geothermal systems, the main advantage of mine-based systems is that the mine voids already exist, which reduces the drilling and well maintenance costs. Coal mines are the best and most common mine choices for geothermal exploitation owing to their broad-based accessibility.

Open mine systems have a higher heat exchange efficiency than closed systems since the heat carrier medium is directly in contact with the surrounding ground. These systems generally need a heat exchanger to prevent contact between the mine water and the heat pump. When reinjection is not performed and the used mine water is discharged into the environment, water treatment may be required. If there is a risk of fluid discharge, or there is no accurate information about the mine water’s properties, the fluid must be reinjected into the source mine.

References: (Banks et al., 2019), (Loredo et al., 2016), (AGFW, 2015), (Bracke, 2018)

7.4.1 2008: Mijnwater, Heerlen, the Netherlands

Commissioned in 2008, the Dutch city of Heerlen enjoys a sustainable district heating system developed under the Mijnwater project. The heating system includes geothermal wells to transfer heat from an abandoned coal mine. The basic idea was to investigate how the mine water of an unused coal mine could be regarded as a geothermal source. A mine's corridors contain water at low temperatures. This heat source provides heating as well as cooling to end users thanks to the low-temperature district heating system.

The facility encompasses two warm wells with a depth of 700 metres, two cold wells with a depth of 250 metres, and one additional well with a depth of 350 metres for injecting the return water. The temperature of the warm, cold, and return water is 28°C, 16°C, and 18-22°C, respectively. The three-pipe distribution network, with a trench length of 7 km, transmits heat to the substations of the connected buildings. The three pipes comprise one insulated pipe to deliver warm mine water, one non-insulated pipe to deliver cold mine water, and one non-insulated return pipe to return the used mine water to the injection well. Heat pumps are used in buildings to meet the heating and cooling loads at the needed temperatures. This case is on the same site as case 5.3.1.

Links:
https://mijnwater.com/en/
https://reader.elsevier.com/reader/sd/pii/S187661021400174X

7.4.2 2017: Gateshead Energy Centre, Gateshead, United Kingdom

The Gateshead Energy Centre was opened in 2017 to provide heat and power to the district energy network across Gateshead's town centre and the Gateshead Quays area. The low-carbon energy centre generates heat and power for sale directly to customers through a new 5 km underground network of heat pipes and high-voltage private-wire electricity cables. At first, the scheme supplied public buildings and homes. However, as new customers connect, the system continues to grow requiring a corresponding increase in the energy supply.

The scheme aims to reduce the carbon dioxide emissions from the energy supplied to customers and achieve carbon neutrality by 2030. The installed gas-powered CHP engines were the first step towards a zero-carbon future. The company has a five-year business plan to reduce emissions. The plan includes building and operating two 3 MW mine water heat pumps to supplement the network with heat recovered from abandoned mineworking. The plan to use mine water for a cooling network to supply nearby developments will be developed to also provide zero carbon cooling.

Link:
https://www.gateshead.gov.uk/article/2994/District-Energy-Scheme-benefits

7.4.3 Planned: Gardanne, France

REWARDHeat is a European project aimed at demonstrating a new generation of low-temperature district heating and cooling networks to recover low-temperature renewable and excess heat. Part of the project involves taking advantage of a closed coal mine, now filled with water, as a source of geothermal heat. This case is located in the city of Gardanne, France. The old coal mine, which closed in 2003, reaches a depth of 1 100 metres, making it the deepest mine shaft in Europe. The mine shaft works as a geothermal heat source with a capacity around 500 kW. It can also operate as a seasonal heat storage unit with a 65 000 m^3 capacity to store water. Half of the 1.3 km long piping network has been completed, with three substations currently functioning and other substations that were planned to become operational by 2023.

Links:
https://www.rewardheat.eu/en/Demonstration-Networks/Gardanne
https://geoera.eu/wp-content/uploads/2021/01/Task_2.4_FS_7.pdf

7.4.4 Proposed: South Tyneside Council, Hebburn, United Kingdom

Hebburn was one of three renewable energy schemes managed by the South Tyneside Council. It was a £8 million scheme to extract geothermal heat from abandoned flooded coal mines in Hebburn. In October 2022, the council announced that the programme could no longer progress in its current form due to a stability problem encountered while drilling one of the boreholes. The issue had already been highlighted, and the council asked for more funding as the drilling was still expected to be completed successfully.

The plan was to construct wider abstraction and reinjection boreholes for the permanent drill casings. One borehole was extended successfully; however, stability issues were discovered in the second borehole at a depth of 168 metres. This prevented the well from reaching its target depth of 300 metres. Subsequently, it became clear that the water could not be extracted and returned to the mine workings as intended. The main reason for this is that no new tests or surveys could be conducted, so the analysis was based on historical maps lacking details. Eventually, the plan was changed to use air source heat pumps instead of mine water pumps to feed into the energy centre. Nevertheless, the use of mine water is still being pursued through the revised scheme, which aims to explore the possibility of extracting and reinjecting water using just one borehole. However, this is expected to result in less output from the mine water than originally envisaged.

Link:
https://www.geplus.co.uk/news/south-tyneside-energy-scheme-fails-to-tap-into-geothermal-energy-from-old-mines-11-10-2022

7.5 GEOTHERMAL HEAT FROM SHALLOW GROUNDS

Solar radiation, seeping rainwater, and the air temperature contribute to store heat in the ground near the surface. This heat, which is called shallow geothermal heat, can be extracted when needed, especially in cold months. The heat transfer medium in the collectors extracts the heat from the ground and transfers it to a heating network. The term shallow, like the term deep in deep geothermal, refers to the depth of the heat absorbers. There is no unique definition for shallow and deep geothermal heat. In most countries, depth separation is regulated based on drilling requirements. For shallow depths (usually down to around 500 metres), the main advantage is low drilling costs, which make shallow depth systems affordable to private households.

Shallow geothermal systems usually operate at temperatures between 0°C and 30°C, which is considered the atmospheric ambient temperature. For this reason, shallow geothermal is also called geothermal ambient heat. Some references extend this temperature range to 0-100°C, specifically below 100°C in the case of low enthalpy and below 25°C in the case of very low enthalpy. The thermal capacity of a shallow geothermal plant is usually low, below 5 MW. While the direct use of heat is possible in deep geothermal systems, shallow geothermal systems use heat indirectly as they require a heat pump to upgrade the temperature to be suitable for space heating and preparation of domestic hot water.

Unlike deep geothermal, shallow geothermal supports cooling (either directly or through refrigeration machines), making it very appealing in urban areas. Using heating and cooling simultaneously creates additional synergy effects that can boost the efficiency of heat pumps and chillers, as addressed in Sections 8.7 and 8.8.

Links:
https://geoera.eu/blog/muse-differences-between-deep-and-shallow-geothermal-energy/

7.5.1 2011: Agrothermie, Wüstenrot, Germany

In 2011, a horizontal heat exchanger and a low-temperature district heating network were integrated for research purposes in the municipality of Wüstenrot. The development continued in the following years. In 2019, the surface of the horizontal geothermal collector distributed over two layers in the town of Bad Nauheim reached 22 000 m^2. This system meets the heating and cooling demands of around 1000 people in 400 residential units via a low-temperature district heating and cooling network, which is about 6 km long. The system use an agrothermal collector: heat is extracted from a very shallow geothermal source without disrupting the agricultural operations on the farmland above the collectors. Depending on the intended heat usage, a heat pump or chiller is needed to provide the desired temperature. Since the required temperature is obtained after the heat extracted from the ground reaches the user, the heat loss is very low, especially compared to high-temperature district heating systems.

Reference: (Brennenstuhl et al., 2019)

7.5.2 2022: Sigtuna Stadsängar and EON, Sigtuna, Sweden

Sigtuna Stadsängar is developing a sustainable neighbourhood in the Swedish town of Sigtuna based on a combination of different renewable energy sources. One of the sources is a shallow geothermal heat field of 120 boreholes which were connected to a low-temperature district heating network in 2022. Geothermal heat partly powers the heat pumps to reduce the amount of the electricity needed. Additionally, large air collectors increase the temperature of the fluid circulating through the geothermal reservoir. The electricity for the heat pumps is provided by solar cells.

Links:
https://www.mynewsdesk.com/se/sigtunastadsangar/pressreleases/eons-unika-naervaermeanlaeggning-i-stadsaengarna-invigd-3167203
https://www.energi-miljo.se/bergsaker-varme-fran-uteluft/

7.5.3 Planned: N-Ergie, Nürnberg, Germany

N-ERGIE plans to carry out the first shallow geothermal heat project in the Kornburg district in Nürnberg. The installation will be one of the largest plants of its kind in northern Bavaria. Owing to the local soil conditions, geothermal probes are impractical, and only a near-surface geothermal solution is possible. The heat transfer medium in the pipe collectors gathers low-temperature heat from the ground.

The extracted heat is transferred to 100 houses via a district heating network of around 2.5 km. The temperature of the extracted is only up to 8°C, so buildings must be equipped with heat pumps. Part of the buildings' electricity needs are met by with rooftop solar PV installations. This energy system ultimately achieves a primary energy factor (PEF) of 0.4. Works on the collector and the local heating network started in 2022 and are expected to be completed in 2024. Once the project is completed, the installation of the collector will be invisible, and it will be possible to use the field for agricultural purposes again.

Link:
https://magazin.n-ergie.de/presse/erdwaerme-fuer-rieterbogen-in-kornburg

7.6 SOLAR DISTRICT HEATING

Solar district heating plants comprise large fields of solar thermal collectors that feed their generated solar heat into district heating systems in mostly villages, towns, and smaller cities. During warmer periods, solar thermal plants can replace other sources of heat supply. Advances in large-scale thermal storage have made it possible to store heat in summer for winter use, as described in Chapter 5.

Solar district heating plants can be centralised or decentralised. Centralised plants are typically ground-mounted, covering a large area of land. In decentralised solar district heating, the solar collectors are located outside the central heat supply plants, usually at appropriate locations like buildings, car parks, or small fields, and directly connected to the district heating primary circuit on site. These decentralised plants are often roof-mounted, which can be advantageous in urban areas with high land costs. Solar technology for decentralised district heating can also be combined with other forms of decentralised heat supply. The annual output of useful heat from solar collectors varies between 100 and 500 kWh per square metre of solar collector. This range can be explained by the varying performance of solar collectors, which is affected by solar irradiance, collector temperatures, stratifications in and losses from storage tanks, and control strategies.

At the beginning of 2023, more than 260 European towns and cities were using solar heat in district heating systems. Denmark is the leading country with 125 solar district heating systems and a capacity of around 1125 MW from 1.6 million square metres of solar collectors, followed by Germany with 48 systems and a 100 MW capacity. In recent years, around ten solar district heating plants have been added annually across Europe. With numerous announced plants, a jump in this trend was experienced in 2022. Most of these plants are in the 20-50 MW capacity range.

The introduction, development, and expansion of solar district heating in the European Union have been supported by five dedicated EU research projects (SUNSTORE2, SUNSTORE4, SDHTAKE-OFF, SDHPLUS, and SDHp2m).

References: (Pauschinger, 2016), (Tian et al., 2019), (Lennermo et al., 2019), (Sandrock and Pauschinger, 2019), (Beauvais and Epp, 2023)

Links:
https://task68.iea-shc.org/
https://www.solare-waermenetze.de/2023/06/26/solare-waermenetze-in-deutschland-juni-2023/

7.6.1 1999: Marstal Fjernvarme, Marstal, Denmark

The first solar panels in Marstal, Denmark, were put into operation in 1999 and have been subject to expansion since then. In 2011 and 2012, the SUNSTORE concept was implemented to show that the town's district heating could be supplied by 100% renewable sources, of which more than 50% solar thermal. The overall objective of the SUNSTORE 4 project was to demonstrate a large-scale innovative, cost-efficient, and technically reliable 100% renewable energy supply system for a large-scale district heating system in Marstal. The aim was to supply 28 GWh of annual heat demand of the district heating system by solar and biomass energy, including a carbon dioxide heat pump and electricity production from biomass. The idea of solar heating took shape when the district heating company Marstal Fjernvarme was investigating the use of biofuels instead of waste oil for heating purposes. The plant comprises the following parts:

- 33 400 m2 solar collector field
- CHP system with a low emission 4.0 MW wood chip thermal oil boiler with a 750 kWe organic Rankine cycle
- 75 000 m3 pit heat storage
- 10 300 m3 pilot pit heat storage
- 1,5 MW heat pump with carbon dioxide as a refrigerant

In the summer, the solar system loads the storage and provides Marstal with district heating. From the end of September, the stored heat is supplied along with heat from the wood chip boiler or the heat pump. In the winter, the backup boilers must supply heat for a few hours, and/or the heat pump must run when the electricity price is high. In February, the solar system begins to heat the storage again. The wood chip boiler runs almost full-time until April. This case is on the same site as case 5.5.1.

Link:
https://www.solarmarstal.dk/media/6600/summary-technical-description-marstal.pdf

7.6.2 2007: Drake Landing, Okotoks, Canada

The Drake Landing Solar Community (DLSC) is a master-planned neighbourhood in the town of Okotoks in Alberta that has successfully integrated Canadian energy-efficient technologies with solar energy. The first of its kind in North America, DLSC is heated by a district system designed to store abundant solar energy underground during the summer months and distribute the energy to each home for space heating needs during the winter months. Operating since 2007, an array of 800 solar panels generates 1.5 MW of thermal power during a typical summer day. This pilot project supplies space heating to 52 detached homes through a central heating system powered by solar thermal collectors and a seasonal borehole thermal energy storage (BTES) system. Heat is captured across 2 300 square metres of flat-plate solar thermal collectors mounted on the roofs of detached garages. It is then transferred to the ground through 144 single U-tube borehole heat exchangers, each 35 metres deep, covering a circular area with a diameter of 35 metres. The system had lower solar fractions in its initial five years of operation when the BTES was being charged. In the fifth year, the solar fraction increased to 97% and has remained at around 90% since (notably, it reached 100% in 2015-2016). After the initial charging period, the efficiency of the seasonal BTES has averaged 45%. This case is on the same site as case 5.2.2.

Reference: (Sibbitt et al., 2012)

Link:
https://www.districtenergy-digital.org/districtenergy/library/item/fall_2022/4049842

7.6.3 2009: Gram Fjernvarme, Gram, Denmark

The consumer-owned district heating company Gram Fjernvarme in the Danish town of Gram has expanded its large-scale solar heating plant from 10 000 m² in 2009 to 44 800 m² in 2015. Moreover, it has built a 120 000 m³ seasonal thermal storage pit. The storage allowed the company to increase the share of solar heating from 16% to 61%; the rest of the heat is provided by an electric boiler (15%), a heat pump (8%), industrial surplus heat (8%), and a CHP gas engine (8%)). The plant has around 3 600 panels resulting in a total capacity of 31 MW. The annual heat production is estimated to be 18 GWh, corresponding to a 50% coverage of the heating plant's annual production. The solar facility prevents 3 700 tonnes of carbon dioxide emissions. This case is on the same site as case 5.5.3.

Link:
http://www.gram-fjernvarme.dk/firmaprofil/solvarme-i-gram

7.6.4 2012: Vojens Fjernvarme, Vojens, Denmark

Vojens Fjernvarme added in 2015 a 52 500 m² solar collector field to its 17 500 m² system built in 2012, achieving a 70 000 m² solar collector system. The system was combined with pit heat storage of 203 000 m^3 to improve the solar system's performance. The plant meets 45% of the heating needs of 2 000 district heating customers in Vojens, Denmark. The project was expected to give customers 10-15% bill savings and save the environment 6 000 tonnes of carbon dioxide emissions annually. The heat storage is charged from April to mid-September by pumping water at 80-90°C into the top of the storage. By September, the storage is fully heated at around 80-90°C almost to the top and 40-60°C at the bottom. Alongside charging the storage, the solar heating system covers the ongoing heat demand of the district heating network. This case is on the same site as case 5.5.4.

Link:
https://ing.dk/artikel/her-er-verdens-stoerste-varmelager-og-solfanger

7.6.5 2014: Dronninglund Fjernvarme, Dronninglund, Denmark

Since 2014, Dronninglund Fjernvarme has been using solar panels to provide heat for the district heating network in Dronninglund. The main components in the heat production facility are a large solar thermal plant and a pit heat water storage unit. In the summer, the solar thermal plant produces much more heat than Dronninglund needs. The surplus is used to heat the water storage. In the autumn, the storage is cooled by adding water with the district heating return temperature to the bottom of the storage and sending hot water from the top of the storage to the city. The district heating return temperature is approximately 40°C. To utilise the storage further, it is cooled down from 40°C to 10°C with a heat pump. This increases the storage capacity before the next summer, reduces heat loss, and increases the amount of solar heat extracted from the solar collectors.

The solar thermal plant comprises around 3 000 solar collectors, equivalent to 37 600 m^2, from Arcon Solar. The collectors are divided into fields, each connected to a heat exchanger in the interface building. The maximum capacity output from the collector fields is 26 MW, while the maximum demand in the network is 12 MW in the coldest winter periods. The cold water is heated gradually through the solar collectors. This ensures that the temperature in the last solar collector of the sequence is decided in the control system. The solar collectors are mounted on galvanised steel profiles processed into the ground.

During the winter, if the solar collectors can produce water with temperatures above the temperature at the bottom of the storage, the solar collector pumps will start, and the storage will be heated. During the summer, the flow from the solar pumps is regulated to ensure that the extraction temperature exceeds the district heating supply temperature, which is approximately 75°C. When the extraction temperature is higher than the supply temperature in the city, the storage is heated by adding hot water to the top and removing cold water from the bottom.

Link:
https://www.dronninglundfjernvarme.dk/media/2984/brochure_dronninglund_2015_booklet_eng_web_.pdf

7.6.6 2014: Lerum Fjärrvärme, Lerum, Sweden

In 2014, a solar district heating system consisting of Aquasol Big 13L collectors was installed in the Swedish municipality of Lerum. The plant has a temperature-controlled system, and with one long row, its solar collectors occupy an area of 857 m2. This case is in the same site as case 4.8.1.

Reference: (Lennermo et al., 2019)

7.6.7 2016: Silkeborg Forsyning, Silkeborg, Denmark

In 2016, Silkeborg Forsyning built a district heating solar thermal plant in the town of Silkeborg. This is currently the largest solar thermal plant connected to district heating in the world. Its 156 700 m^2 solar collector field meets the entire summer district heating demand of the city. With a maximum capacity output of 110 MW, annual heat extraction of 80 GWh, and flow of 2 700 m^3/h, the plant provides green heat to 21 000 district heating consumers and covers the annual heat consumption of 4 400 households. This corresponds to supplying 20% of Silkeborg's total annual heat demand. The plant is part of the municipality's ambition to supply exclusively decarbonised heat by 2030.

Link:
https://www.tv2ostjylland.dk/tv-midtvest/verdens-storste-solvarmeanlaeg-taget-i-brug

7.6.8 2016: Stadtwerke Senftenberg, Senftenberg, Germany

In August 2016, a solar thermal system was commissioned at a former landfill site in Senftenberg. With a collector area of 8 300 m^2, it was the first real large-scale vacuum tube collector system in Germany to provide heat for a district heating network. The planning of the plant was carried out by Ritter XL Solar, which also supplied the complete collector field comprising 1 680 high-performance collectors. The annual heat production is around 4 GWh, corresponding to 4% of the total amount of heat delivery. The district heating network of the company has a total trench length of around 33 km. The supply/return temperatures are 85/65°C in summer and 105/55°C in winter. The large-scale solar system was designed in such a way that it could supply the entire heat requirement of the network on normal summer days.

Link:
https://www.ritter-xl-solar.de/anwendungen/waermenetze/stadtwerke-senftenberg

7.6.9 2017: Ystad Energi, Ystad, Sweden

In 2017, a solar district heating system consisting of 36 Savo 15 SG collectors was installed in the southern Swedish city of Ystad. The plant has a flow-controlled system and has 534 m^2 solar collectors on a rooftop. The municipality-owned energy company Ystad Energi owns and maintains the facility and feeds its district heating network with clean thermal energy. This case is on the same site as in case 4.8.2.

Reference: (Lennermo et al., 2019)

7.6.10 2019: Salaspils Siltums, Salaspils, Latvia

In September 2019, the district heating operator Salaspils Siltums inaugurated a 21 700 m² solar field and a wood chip boiler in the Latvian town of Salaspils to meet 90% of the demand of the local district heating network. The collectors were delivered by the Danish manufacturer Arcon-Sunmark, while the Latvian-based company Filter installed the system. The inauguration took place after a three-week test run of the solar district heating plant and its new 8 000 m³ storage tank. Salaspils Siltums started planning the solar system after a neighboring cogeneration plant was phased out. The project has received 2.73 million euro from the EU’s Cohesion Fund, while the total investment in the solar field, the storage tank, and the 3 MW biomass boiler was 7.08 million euro. The project could reduce the company’s district heat tariff by at least 5%.

Link:
https://www.solar-district-heating.eu/15-mw-sdh-plant-inaugurated-in-latvia/

7.6.11 2021: Härnösand Energi och Miljö, Härnösand, Sweden

The Absolicon solar collector park started operating in Härnösand, Sweden, in the summer of 2021. At this stage, the first part of the plant started working with an approximate capacity of 0.5 MW. The park will have an area of 3 000 m² and an output of 1.5 MW after an extension in 2023. The annual production of the entire facility will be approximately 1 GWh. The park will be gradually connected to the district heating network, which is operated by the local energy company Hemab. Absolicon's technology uses a silver mirror that concentrates sunlight in a tube of pressurised water. The mirror follows the sun during the day, and the technology can generate temperatures up to 160°C. However, the plant in Härnösand has been designed to deliver 120°C. On a sunny summer day, the solar thermal park should be able to meet around a quarter of Härnösand's heat demand.

Link:
https://www.energi.se/artiklar/2021/maj-2021/solpark-kopplas-in-i-harnosands-fjarrvarmenat

7.6.12 2021: Newheat, Narbonne, France

In autumn 2021, the Narbosol solar district heating plant with 2.8 MW capacity was commissioned by the renewable energy company Newheat in Narbonne. The total area of the collector field is over 3200 m² and the collectors are supplied by the Finnish solar company Savosolar. A 1000 m³ heat storage unit has supplemented the facility. The annual production is about 2.3 GWh to supply a district heating network of 900 houses, seven schools, and several public buildings. Narbosol is expected to produce a total carbon footprint of only 730 tons of carbon dioxide equivalent over its 25-year cradle-to-grave life cycle. Accordingly, each kWh of solar heat produced by Narbosol emits the equivalent of 12 g of carbon dioxide. Based on the assessments, Narbosol’s equipment accounts for 74% of the total carbon footprint, followed by energy consumption, freight, the end-of-life of equipment, and transportation.

Link:
https://solarthermalworld.org/news/small-carbon-footprint-of-large-solar-field-in-france

7.6.13 2021: AbSOLAR, Cadaujac, France

In late 2021, Savosolar delivered a solar thermal system to AbSOLAR SAS to supply heat for a district heating network in Cadaujac, France. The delivery included a turn-key solar plant with a solar collector field, piping, a solar station, and automation. The 950 m² collector field consists of Savo 15 SG collectors. The project was part of a 100% renewable energy solution where the solar thermal plant was combined with a seasonal borehole thermal storage from AbSOLAR to supply heating and domestic hot water to 67 newly built single-family houses connected to the heat network. The energy mix is intended to be more than 95% from solar thermal, making it almost free of carbon dioxide emissions. The total value of the project is approximately 0.3 million euro.

Links:
https://savosolar.com/cases-en/cadaujauc
https://savosolar.com/savosolar-hands-over-solar-district-heating-system-in-cadaujac-france

7.6.14 2022: Stadtwerke Greifswald, Greifswald, Germany

In September 2022, the Stadtwerke Greifswald company put into operation its 18 700 m² solar thermal system consisting of evacuated tube collectors for the district heating network in Greifswald, Germany. This is currently the largest solar thermal system in Germany. Compared to flat-plate collectors, a higher annual performance is expected from the system’s evacuated tube collectors. The solar thermal system is designed to generate around 8 GWh annually, corresponding to a contribution of more than 3% of the total heat supply in the city.

The thermal output of the solar thermal system is around 11 MW in summer, which covers the base load. Surpluses are temporarily buffered by means of heat storage. The solar thermal system is combined with an electrode boiler and a CHP plant. A large-scale heat storage facility with a storage capacity of 6 000 m³ will complement the existing heat storage in 2024 and be integrated into the district heating network. This means that more heat will be stored and used at times of the year when the solar radiation is low. Thus, the percentage of renewable district heating in Greifswald will be increased significantly to around 20%.

Link:
https://www.solare-waermenetze.de/2022/09/28/groesste-solarthermieanlage-deutschlands-in-greifswald-in-betrieb-gegangen

7.6.15 2023: Warmtestad, Groningen, the Netherlands

In November 2022, the construction of a planned 37 MW solar district heating plant began in Groningen, which will be the world's fourth-largest solar district heating field. The annual heat production will be 25 GWh. The 48 000 m² collector field will be connected to Groningen's district heating network, which is operated by the utility company Warmtestad. The collector field, including the technical building and a 6000 m^3 storage tank, will occupy 12 hectares. Three companies collaborated on this project: Solarfields (Netherlands), as the project developer, K3 (Netherlands), as the investor, and TVP Solar (Switzerland), as the provider of the solar turnkey field.

The collector field will consist of high-vacuum flat plate collectors that reach the required temperatures beteen 69°C and 93°C year-round. A long-term solar heat delivery contract for 30 years has been signed by Warmtestad. The solar thermal plant supports the ambition of the municipality of Groningen to become carbon neutral by 2035. Once completed, the solar heat plant will cover 25 % of the total heat demand of 10 000 connected households and other private and public buildings in the northwest of Groningen. Commissioning is planned for October 2023. The solar plant will achieve a annual average solar thermal efficiency of 52% and feed heat directly into the network even in the winter and in sub-zero conditions.

Link:
https://solarthermalworld.org/news/37-mw-solar-district-heating-plant-in-the-netherlands-with-outstanding-features

7.6.16 Planned: Pristina, Kosovo

A feasibility study is underway to build a solar thermal district heating in Pristina, Kosovo to create a capacity of 40.6 MW on an area of 58 000 m^2. The plan is supplemented by a seasonal storage with 408 000 m^3 capacity. Absorption heat pumps heat up the water from the seasonal storage tank if it does not meet the demand of the supply pipe for the heating network. This case is in the same site as case 4.10.2.

Reference: (Beauvais and Epp, 2023)

7.6.17 Proposed: Big solar Graz, Graz, Austria

In 2014, the city senate of Graz, Austria, started a project to identify alternatives to fossil fuels to provide 80% of the heat supply to the Graz district heating system. Approximately 120 000 people in the city are supplied by district heating, resulting in an annual district heating demand of 1 200 GWh.

Various simulations indicated that it is technically feasible to build a large-scale solar thermal system with seasonal pit storage and absorption heat pumps. The size of the solar system was estimated to be 450 000 m^2 with a 250 MW capacity and an annual heat output of 245 GWh. Regarding the project's economic feasibility, the assessments indicated that the price of heat from the proposed system would be competitive compared to the price heat from gas boilers. This case is on the same site as case 4.10.3.

Reference: (Reiter et al., 2016)

Link:

https://www.irena.org/-/media/Files/IRENA/Agency/Events/2020/Apr/Technology-specific-focus-Challenges-Christian-Holter.pdf

7.6.18 Proposed: Salzburg Energie, Salzburg, Austria

A feasibility study has been carried out for a large solar thermal plant with seasonal heat storage connected to the district heating system in Salzburg. The aim is to decarbonise the energy supply mix and reduce the dependency on energy imports. The realisation of the proposal would lead to the largest solar thermal plant in Central Europe, with an area of 45 000 m^2 and a heat supply of 20 GWh per year. Seasonal storage tanks and absorption heat pumps would be used to integrate the heat sources in the proposed solar thermal plant. The seasonal storage unit is supposed to have a capacity of about 65 000 m^3.

Link:
https://thermaflex.greenenergylab.at/e4a_demonstrator/big-solar-salzburg/?lang=en

7.7 ELECTRICITY

Using electricity as an energy source for district heating corresponds to the power-to-heat concept, which refers to the use of electricity for heating purposes, primarily through heat pumps and electric boilers. Large-scale solutions for power-to-heat applications require a district heating system for heat distribution and offer advantages such as integrating higher proportions of renewable energy, absorbing surplus electricity at lower costs, and utilising strategic heat sources for heat pumps.

Power-to-heat solutions in district heating systems have been historically used during periods of surplus electricity. An early example is the use of surplus electricity from early hydropower plants to provide electric heating for buildings and some early district heating systems. These surpluses appeared during wet years with more rainfall than average. The substitution idea of using electricity for heating purposes was seriously pursued in Sweden, Norway, and Germany during the 1910s and 1920s.

The second wave of power-to-heat developments occurred in Sweden during the 1980s, when the electricity demand did not grow according to the national expansion plans from the nuclear power programme. A surplus of nuclear power appeared in the electricity market; at the same time, oil prices were high in the aftermath of the second oil crisis in 1979-1980. This situation provided a national opportunity to use the nuclear power surplus for to substitute fuel oil in both individual heating systems and district heating systems. Over a few years in the early 1980s, the installed capacity of large electric boilers in industrial and district heating systems experienced a significant increase in Sweden, reaching approximately 3400 MW.

The adoption of large heat pumps in the Swedish district heating systems also gained momentum in the 1980s through the use of low-temperature heat sources, such as treated sewage waters, ambient water resources, and industrial excess heat.

The total heat output from large heat pumps exceeded 1500 MW. With its nuclear power surplus, Sweden became a global leader in installing large heat pumps and electric boilers in district heating systems.

The third wave is happening now as the proportion of wind power is increasing rapidly in the European electricity market. During windy days, lower electricity prices are experienced. The huge European expansion plans for wind power in the North Sea were expressed in the Ostend Declaration on 24 April 2023 by the energy ministers of nine countries: Belgium, Denmark, France, Germany, Ireland, Luxembourg, The Netherlands, Norway, and the United Kingdom. The commitment is to provide at least 130 GW by 2030 and 300 GW by 2050. This is a major expansion of the current EU offshore wind power capacity of 15 GW.

These expansion plans for wind power will amplify the price variations in the European electricity market, providing another opportunity in northwest Europe for electric boilers and large heat pumps in district heating systems, especially those with large heat storage capacities. This recent trend is visible in the eight cases presented below, which focus on the use of electric boilers.

References: (Lund et al., 2014), (Hers et al., 2015), and (Averfalk et al., 2017).

Links:
https://www.euractiv.com/section/energy/news/germany-denmark-netherlands-and-belgium-sign-e135-billion-offshore-wind-pact/
https://www.montelnews.com/news/1350368/north-sea-countries-target-76-gw-of-offshore-wind-by-2030
https://www.government.nl/documents/diplomatic-statements/2023/04/24/ostend-declaration-on-the-north-sea-as-europes-green-power-plant
https://cipartners.dk/2022/10/25/orsted-and-copenhagen-infrastructure-partners-join-forces-to-develop-approx-5-2-gigawatts-of-offshore-wind-in-denmark/
https://www.danskfjernvarme.dk/-/media/danskfjernvarme/gronenergi/analyser/ptx/power-to-x-and-district-heating_english-version_web.pdf
https://www.dn.se/ekonomi/vindrevolutionen-i-ostersjon-nya-kraftverken-flyter-pa-plattformar/

7.7.1 2015: Stadtwerke Kiel, Kiel, Germany

A 35 MW electrode boiler has been implemented in the first phase of a project by Stadtwerke Kiel on the Baltic Sea coast in northern Germany. The aim was to combine highly efficient gas-engine-based CHP with thermal storage and a power-to-heat electrode boiler to increase operational flexibility. This initial phase included the installation of a 60 metres high heat storage unit, the electrode boiler, and a pump house that connects the facility to the Kiel district heating network. The power-to-heat electrode boiler enables the excess electricity in the grid during periods of low electricity prices to be used to produce heat, stored in thermal storage, or supplied to the district heating network. The electrode boiler allows the facility to participate in the secondary balancing market, which is another valuable source of revenue.

Link:
https://www.modernpowersystems.com/features/featurepreparing-for-the-next-phase-at-stadtwerke-kiels-super--flexible-multi-purpose-plant-5665710

7.7.2 2015: Kredsløb, Aarhus, Denmark

AffaldVarme Aarhus (now part of Kredsløb) inaugurated an 80 MW electric boiler in April 2015 as a quick and cheap-to-build backup boiler option. In its first year of operation, the boiler ran for 900 hours, mainly during cheap electricity periods. It generated 76 GWh of heat, which provided a reduction in the overall cost of heat generation.

Link:
https://fjernvarmen.danskfjernvarme.dk/p/magasinet-fjernvarmen/2016-10-18/r/23/44-45/3045/370437

7.7.3 2018: Hamburg Wärme, Hamburg, Germany

In 2018, Hamburg Wärme replaced the electrode boiler located inside the electric power transformation substation at the Karolinenstraße, Germany, after its main components reached the end of their service life. The purpose of the renewal was to replace the old electrode steam boiler system with a warm water electrode boiler with new ancillaries, transformers, substations, and control systems.

The new 45 MW electrode boiler works as a short-term and flexible ready-to-use heat generation system. It is mainly used as a peak load heat generator to support the district heating network during the heating season. Furthermore, as a power-to-heat system, the boiler will be part of the German research programme SINTEG to provide heat for the district heating network in case of a short-term oversupply of electricity generated by wind turbines. The plant can be operated based on the electricity prices on the spot market or as a fast and considerable reserve for the electricity network.

Link:
https://www.wg-ing.de/en/projects/cogeneration-plant-karoline-elektrokessel-waerme-hamburg-gmbh

7.7.4 2019: Vattenfall, Berlin, Germany

The Vattenfall company uses excess renewable electricity as an energy source for electric boilers to produce heat for the district heating system in Berlin. In 2019, the company connected a power-to-heat facility to the district heating network. With a 120 MW capacity, the facility is currently the largest of its kind in Europe. The boiler uses excess electricity generated from renewable sources to generate an amount of heat equal to the water boilers of 60 000 households.

Link:
https://group.vattenfall.com/press-and-media/pressreleases/2019/vattenfall-inaugurates-europes-largest-water-boiler-for-heat-distribution-in-berlin

7.7.5 2021: Karamay Thermal Power Co, Karamay, China

In China, it is necessary to coordinate coal and wind power plants, especially when the coal power plants have low loads. To avoid closing the coal plants, this grid balancing problem is solved by using electric boilers to utilise the high electricity outputs from wind plants. The heat generated by the boilers is then fed into district heating systems, (Zhang et al., 2021). Six electric boilers with a total capacity of 300 MW were installed in 2021 at the Karamay thermal power plant in the Xinjiang province. These boilers were supplied by the Swedish company Elpanneteknik, which has delivered electric boilers with a total capacity of about 2000 MW to China.

Link:
https://elpanneteknik.com/2015/04/03/balancing-grid-through-emission-free-district-heating

7.7.6 2022: Fjernvarme Fyn, Odense, Denmark

Fjernvarme Fyn achieved a big milestone in 2022 by turning on another 50 MW electric boiler in Odense. As a result, there are now two large electric boilers in Havnegade that together provide 100 MW of heat to supply the local district heating network. This capacity corresponds to the heat consumption of 5 000–10 000 ordinary households on a cold day. The electric boilers typically work when the electricity generation from wind turbines and solar cells is particularly high.

Link:
https://www.fjernvarmefyn.dk/nyheder/uofficiel-Danmarksrekord-paa-100-MW-varmeproduktion-med-elkedler

7.7.7 2023: DIN Forsyning, Esbjerg, Denmark

DIN Forsyning used to purchase more than half of its heat supply from Ørsted, which generated excess heat at Esbjergværket Blok 3 (ESV3). When Ørsted closed ESV3 in March 2023, it became necessary for DIN Forsyning to find a new heat supply. The goal was to implement a heat supply system that economically benefits heat consumers in the Danish cities of Esbjerg, Nordby, and Varde. In addition, the new district heating system should be green, flexible, and based on mature technologies. An electric boiler became a part of the solution. The nominal power of the boiler is 40 MW. However, the effective power output is expected to be lower since there are other components using electricity and the maximum power that can be drawn from the grid is currently 39 MW (this will increase to 50 MW in the future).

Link:
https://fremtidensfjernvarme.dk/da-dk/projekt-p%C3%A5-havnen/elkedel

7.7.8 Planned: Vattenfall, Amsterdam, the Netherlands

Vattenfall has been granted a permit and a subsidy to install a 150 MW power-to-heat electric boiler at the company's heat and power plant in Diemen, Amsterdam. The final investment decision was scheduled for mid-2022. The system is expected to be operational by early 2025. The boiler only switches on if the electricity mix is deemed sustainable, with significant electricity from solar and wind sources. Vattenfall aims to supply 100% sustainable heat in the Amsterdam region by 2040.

Link:
https://www.parat.no/news/vattenfall-invests-in-large-eboiler-system-in-amsterdam

7.8 AMBIENT HEAT FROM SEA AND LAKE WATER

Ambient heat stored in sea, lake, and river waters is a renewable and reliable local energy source. By harnessing this heat, the need to burn fossil fuels to generate heat can be significantly reduced. Seas and lakes naturally absorb heat from the sun and the air during spring and summer, releasing it back into the atmosphere in the autumn and winter. The temperature of these water sources follows seasonal cycles, only with a smaller amplitude and time lag compared to air temperature cycles. This feature makes them an effective heat source or sink in various regions worldwide.

In Europe, lakes often have lower deep-water temperatures than the ambient air during summer, making them suitable for cooling, and higher temperatures during winter, making them suitable for heating, especially in countries with high heat demands.

Five cases are presented below where water-based heat is extracted by heat pumps for heat supply into district heating systems.

References: (Gaudard et al., 2019), (Eggimann et al., 2023)

7.8.1 2011: Drammen Fjernvarme, Drammen, Norway

Since 2011, the municipality of Drammen in Norway has been using seawater to provide district heat for the town. Three large heat pumps with ammonia as refrigerant and total heat capacity of 13.5 MW extract heat from a nearby fjord which has a water temperature of about 8°C at a depth of 18 metres year-round. The heat pumps can deliver a temperature of up to 90°C and annually provide 67 GWh of heat, covering the heating needs of around 6 000 homes. The heat pumps in Drammen have replaced a mixture of fuel oil, biomass, and electric boilers.

This heat pump plant is currently being expanded with two heat pumps of 9 MW each from the Swiss company Friotherm. Commissioning is expected in the spring 2024 and the refrigerant will be HFO1234ze, a fourth generation refrigerant, rather than ammonia.

Links:
https://www.sitra.fi/en/cases/district-heating-from-seawater-drammen
https://energiteknikk.net/2023/11/drammen-fjernvarme-storst-pa-sjovarme

7.8.2 2023: DIN Forsyning, Esbjerg, Denmark

DIN Forsyning has implemented a large seawater-based heat pump in Esbjerg, Denmark, with a nominal capacity of 60-70 MW and carbon dioxide as refrigerant. The seawater heat pump system is electrically powered and produces district heating by cooling the seawater to a maximum of 4°C at the outlet. It is planned to operate from September to May when provided with the right electricity price and temperature conditions for achieving the lowest possible production cost. The intention was to commission the plant in 2023.

Heat is extracted from the seawater to heat the district heating water to approximately 65°C degrees, which is the required temperature for customers. If a zone needs a higher temperature, the water is sent to another unit for additional heating. The pump will use approximately 4 cubic metres of seawater per second. The facility will annually generate about 235 GWh of heat, of which 170 GWh come from seawater cooling and 65 GWh are supplied using electrical energy. The seawater inlet will have filters to sort out driftwood and other foreign objects and protect fish from harm. No chemical cleaning or pesticides will be used to clean the facility.

Links:
https://fremtidensfjernvarme.dk/da-dk/projekt-p%C3%A5-havnen/havvands-varmepumpe
https://www.man-es.com/docs/default-source/document-sync/esbjerg-heat-pump-reference-case-eng.pdf
https://www.districtenergy-digital.org/districtenergy/library/item/q3_2023/4120256/
https://addedvalues.eu/c/nyheder/havvandsbaseret-varmepumpe-bliver-hjertet-i-fremtidens-fjernvarmeforsyning-i-esbjerg
https://addedvalues.eu/c/nyheder/derfor-er-havvandsvarmepumperne-saa-fascinerende

7.8.3 Planned: HOFOR, Copenhagen, Denmark

HOFOR intends to build a new energy centre in Nordhavn, Copenhagen. The energy centre will house a wastewater pumping station, a district cooling centre, and a large heat pump for district heating. The heat pump will use seawater and will be the company's largest heat pump to date with its 20 MW capacity. Following a stage of urban development in Nordhavn, the heat pump is expected to be operational in 2028.

This case is linked to case 8.7.6, since the plant is planned to operate in combined heating and cooling mode.

Link:
https://www.hofor.dk/pressemeddelse/ny-energicentral-huser-baade-varme-kulde-og-spildevand/

7.8.4 Proposed: Salmisaari, Helsinki, Finland

The Helen company plans to build a tunnel system as part of a seawater heat recovery system at the Salmisaari site in Helsinki. The development phase is expected to last until autumn 2024. After the development phase, the implementation phase will last approximately five years, and commissioning is expected in 2029. The heat recovery system will supply seawater to heat pumps with a total capacity of 500 MW. The heat pumps will use seawater with a temperature as low as 2°C seawater and electricity for the compressors. The customers will receive the heat via the urban district heating network. In addition, the heat pumps can be used during the summer to generate cooling for the district cooling network.

Link:
https://www.helen.fi/en/news/2022/helen-to-become-alliance-partners-together-with-yit-and-acciona-in-seawater-heat-recovery-project

7.8.5 Proposed: Rheinenergie, Köln, Germany

In June 2023, Rheinenergie announced that they started the planning process for implementing a large heat pump plant with a total heat capacity of 150 MW. The heat source will be the Rhein River and the heat sink will be the district heating system in Köln.

Links:
https://www.rheinenergie.com/de/unternehmen/newsroom/nachrichten/news_70213.html
https://www.energie.de/euroheatpower/news-detailansicht/nsctrl/detail/News/rheinenergie-schreibt-europas-groesste-waermepumpe-aus

7.9 AMBIENT HEAT FROM AIR

Ambient air is a common heat source for individual heat pumps for single-family houses which has been less common in district heating systems. However, in recent years, Denmark has installed a remarkable number of large air source heat pumps in district heating systems. By the end of 2022, these large air source heat pumps had a total heat capacity of 275 MW. This corresponds to about half of Denmark's heat output capacity of 513 MW from large heat pumps.

Both cases presented below for this possibility are based in Denmark.

Link:
https://varmepumpedata.dk/plants/

7.9.1 2021: Svendborg Fjernvarme, Svendborg, Denmark

In 2021, Svendborg Fjernvarme commissioned a 20 MW air-to-water heat pump, the largest in Denmark, capable of providing heat to approximately 8 000 households in a 1.3 million m^2 area. The output in the winter is estimated to be about 20% lower, 16-17 MW. This heat pump, in conjunction with a 25 MW electric boiler, has replaced the local waste-to-energy facility that supplied most of the district heating in Svendborg.

Link:
https://fjernvarmen.danskfjernvarme.dk/p/magasinet-fjernvarmen/2021-03-29/r/11/20-21/3045/396539

7.9.2 Planned: Silkeborg Forsyning, Silkeborg, Denmark

In February 2023, Silkeborg Forsyning announced that they signed a contract for a future 22 MW air source heat pump plant. The plant will contain three parallel units and commissioning is planned for the end of 2024.

Link:
https://fjernvarmen.danskfjernvarme.dk/p/magasinet-fjernvarmen/2023-08-18/a/silkeborg-tager-et-vigtigt-skridt-mod-co2-neutral-fjernvarme/3045/1052833/42142983

7.10 SUMMARY CONCERNING LINEAR RENEWABLE SUPPLY

The main implication from this chapter is that linear heat supply from renewables has many possible implementations. Both high-temperature and low-temperature heat sources can be used; with low-temperature sources, heat pumps are required to reach temperatures suitable for district heating systems and customers' heating systems.

Most new geothermal heat sources in Europe are aquifers in sedimentary bedrocks; other heat sources include volcanic areas, abandoned mines, and shallow grounds. No geothermal heat from crystalline bedrocks has been fed directly into district heating systems to date despite many recent attempts in Finland and Sweden.

Four companies with a fossil industry background have used their skills and experiences from oil and gas exploration to find geothermal heat sources. The Danish company Innargi has agreements with several cities in Denmark, Germany, and Poland to find suitable geothermal sources. Part of Innargi's staff previously belonged to the oil and gas exploration team at the AP Møller Group. The Finnish company St1 has supported the Espoo (7.3.4) and Malmö (7.3.5) cases. The Canadian company Eavor is active in the Geretsried (7.2.12) and Hannover (7.2.13) cases, while the Austrian company OMV has been involved the Vienna (7.2.11) case. Eavor and OMV have also signed a cooperation agreement concerning geothermal heat.

Solar district heating is mainly expanding in villages and small towns. However, in Danish district heating systems, solar district heating has the same market share (about 2%) as solar heat in the global heat market (Lennermo et al., 2019). This suggest that all other countries can expand their use of solar district heating.

The planned expansion of wind power has generated a strong interest in large electric boilers and heat pumps, resulting several implementations related to wind-based linear heat renewable supply.

Linear renewable supply can decarbonise heat by replacing fossil fuels with geothermal, solar, wind-powered boilers, and large heat pumps, thereby lowering the carbon dioxide emissions from heat generation.

The overall assessment of these linear heat supplies from renewables is that many district heating providers struggle to implement them since fossil fuels are still not paying the full price of their environmental damage through climate change, as described in the introduction of this report.

8 Supplying heat: Heat recycling

Heat recycling refers to possibilities in which excess heat that would otherwise be wasted is recycled into district heating systems. When investments are made and the necessary infrastructure is available, heat recycling can substantially reduce operational costs and emissions. The recycled heat is the by-product of different processes. This chapter describes various heat recycling initiatives in 13 distinct possibilities.

The first possibility presents heat recycling from refineries aiming to produce non-fossil transport fuels. The following two possibilities are related to hydrogen, specifically heat recycling from the electrolysis process (possibility two) and hydrogen-fuelled CHP plants (possibility three). Harnessing excess heat from renewable feedstocks supply plants for petrochemical processes constitutes the fourth possibility. The fifth possibility concerns some heat generated in electricity distribution networks. Heat recycling from new low-carbon industrial plants constitutes the sixth possibility.

Space cooling as a heat source is described in the seventh (centralised heat pumps) and eighth (decentralised heat pumps) possibilities. These two possibilities follow the first major European implementation of the combined heating and cooling principle in the Zürich municipal hall in 1937-1938, (Pallua, 2021).

Data centre cooling is also considered a heat source and could be used via air-cooled systems (ninth possibility) or water-cooled systems (tenth possibility). Heat recycling from the growing number of battery manufacturing plants is the subject of the eleventh possibility. The twelfth possibility concerns heat recycling from refrigeration processes in the food supply chain. Finally, the thirteenth possibility deals with heat recovery from sewage treatment plants.

Figure 20 shows the locations of the identified heat recycling cases in the corresponding database.

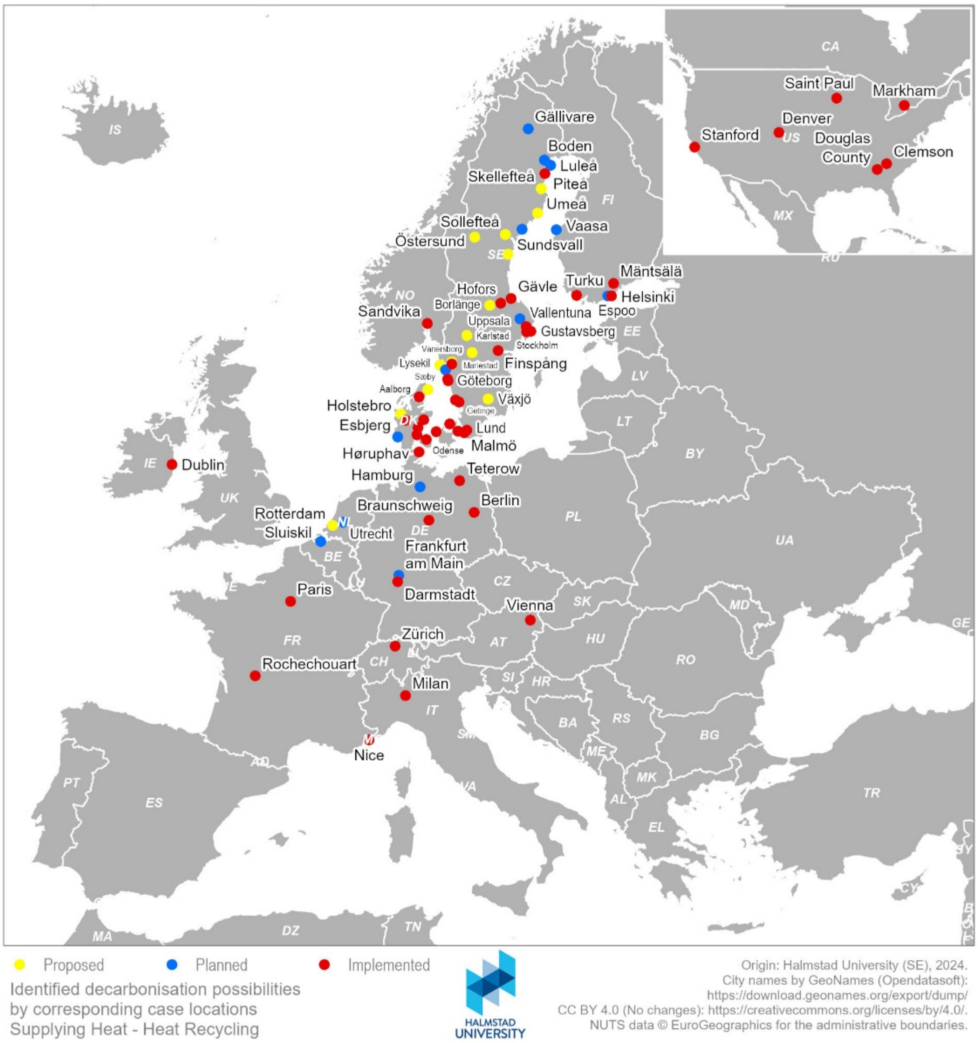

Figure 20. Map showing locations of identified cases concerning heat supply by heat recycling.

8.1 FUEL REFINERIES

Electrofuels, also known as power-to-gas or power-to-liquid fuels, e-fuels, or synthetic fuels are produced by using electricity to combine hydrogen from water (via electrolysis) wih carbon or nitrogen. The production process typically involves mixing hydrogen and carbon dioxide in a reactor to produce an energy carrier. This process enables the production of a variety of liquid and gaseous fuels such as e-methane, e-diesel, and e-petrol.

Electrofuels have garnered attention in the transport sector due to their potential applicability in existing vehicle technologies without necessitating substantial investments in new distribution and fuelling infrastructure. They hold particular significance in sectors like long-distance aviation and deep-sea shipping, where electrification options are limited due to the challenge of finding high-energy-density substitutes for traditional liquid fuels. Additionally, electrofuel production can aid grid balancing during periods of intermittent electricity production by utilising cheap surplus electricity.

The production of electrofuels also results in valuable by-products such as high-purity oxygen and heat. Although the efficiency of energy conversion and utilisation poses a challenge compared to the direct use of electricity. Europe has established several demonstration facilities in the past decade. One of the reasons for this is the possibility of utilising the excess heat from electrofuel production for heating purposes, particularly in district heating networks.

References: (Brynolf et al., 2018) and (Grahn et al., 2022),

8.1.1 2010: Preem and SunPine, Piteå, Sweden

Preem is a co-owner of the company SunPine, which started processing crude tall oil in 2010. SunPine meets almost half of Preem's raw material needs. SunPine's biorefinery in Piteå, Sweden, is another example of innovation to tackle climate change. In 2020, SunPine completed a new factory that increased its capacity to produce sustainable tall oil by 50%. The production of crude tall oil has increased to about 150 000 m³ per year, while the annual emissions of fossil carbon dioxide emission were reduced by about 400 000 tonnes.

Links:
https://www.sunpine.se/en/
https://www.preem.se/globalassets/om-preem/hallbarhet/hallbarhetsredovisning/preem_sustainability-report-2021_01_juni.pdf

8.1.2 2010: Preem, Gothenburg, Sweden

Preem, the largest fuel company in Sweden, has adopted ambitious goals to restructure its operations and attain the large-scale production of renewable fuels. The company has two refineries, one in Gothenburg and one in Lysekil, which are among the most energy-efficient and modern refineries in Europe. The Green Hydro Treater plant has been rebuilt in several steps since 2010 at the Gothenburg refinery and can now produce 100% renewable fuel.

Sweden's largest production facility for renewable fuels was built at the Gothenburg refinery for commissioning in 2023. The new plant, called Green Feed Unit, produces approximately one million cubic meters of renewable diesel and renewable aviation fuel (bio-jet) annually. To achieve maximum resource efficiency at Preem's plants, gas formed during refining is used as fuel in the process, while excess heat is captured and used for district heating. The Preem refinery in Gothenburg is already connected to the local district heating system for heat recycling.

Link:
https://www.preem.se/globalassets/om-preem/hallbarhet/hallbarhetsredovisning/preem_sustainability-report-2021_01_juni.pdf

8.1.3 2021: Preem and Pyrocell, Gävle, Sweden

Preem intends to use sustainable feedstocks in its refineries. Pyrocell and SunPine are two examples of how the company is increasing the amount of sustainable raw materials used in fuel production. Preem owns Pyrocell together with a wood industry company. At Pyrocell in Gävle, located next to a sawmill facility, non-fossil pyrolysis oil is produced from sawdust. The facility is the first of its kind in Sweden. The pyrolysis oil is then refined into renewable diesel and petrol at Preem's refinery plants. Pyrocell's fuel production amounts to approximately 25 000 tonnes of bio-oil per year, corresponding to the annual fuel consumption of 15 000 cars.

Link:
https://www.preem.se/globalassets/om-preem/hallbarhet/hallbarhetsredovisning/preem_sustainability-report-2021_01_juni.pdf

8.1.4 2024: SCA and St1, Gothenburg, Sweden

SCA and St1 have entered a joint venture to produce and sell liquid biofuels. SCA will supply tall oil to the joint venture. A new biorefinery has been constructed on St1's refinery site in Gothenburg, Sweden, and is expected to be operational by mid-2024. The production capacity wil be 200 000 tonnes of liquid biofuels, including 60 000 tonnes of biojet fuel. The facility is designed to optimise the production of renewable hydrotreated vegetable oil (known as HVO) diesel and bio-jet fuel and to use feedstock on tall oil.

Link:
https://www.st1.com/sca-and-st1-enter-joint-venture-to-produce-and-develop-liquid-biofuels
https://bioenergitidningen.se/st1-tar-sikte-mot-skyn/

8.1.5 Planned: Flagship ONE, Örnsköldsvik, Sweden

Ørsted has acquired full ownership of FlagshipONE, the Swedish green electrofuel plant previously co-owned by Liquid Wind and Ørsted. Located in Örnsköldsvik, FlagshipONE is Europe's largest green electrofuel facility to reach a final investment decision. Once the planned FlagshipONE enters operations in 2025, it will produce around 50 000 tonnes of e-methanol annually. The excess heat from the plant will be delivered to the district heating system in Örnsköldsvik.

Links:
https://www.liquidwind.se/news/liquid-wind-announces-full-ownership-transition-to-orsted-of-flagshipone
https://bioenergitidningen.se/orsted-tecknar-avtal-med-carbon-clean-for-koldioxidinfangning-vid-flagshipone/
https://bioenergitidningen.se/europas-storsta-biometanolprojekt-ska-gora-sjofarten-gronare/

8.1.6 Planned: Liquid Wind, Sundsvall, Sweden

Sundsvall Energi will partner with Liquid Wind to provide carbon dioxide for the second commercial electrofuel facility in Sweden with a 100 000 tonnes capacity. Biogenic carbon dioxide from the energy facility will be captured and combined with renewable hydrogen to generate green e-methanol. The facility in Sundsvall will have twice the electrofuel production capacity of FlagshipONE in Örnsköldsvik. With a construction time of approximately two years, the electrofuel is planned to be available by the end of 2025 or early 2026. Excess heat will be recycled into the Sundsvall district heating system.

Links:
https://www.liquidwind.se/news/liquidwind-announces-plans-for-flagshiptwo-sundsvall
https://www.fvb.se/fvb-nytt/stora-mangder-kyla-kravs-till-ny-industri/

8.1.7 Proposed: Jämtkraft, Östersund, Sweden

Bio electro jet fuel (BEJF) is an electrofuel with untapped potential. Its production at CHP plants in northern Sweden, where the supply of renewable electricity is plentiful and growing, can result in greater synergy in existing CHP generation. BEJF is produced through a synthetic process where biogenic carbon dioxide is the primary carbon source and hydrogen from water electrolysis powered by renewable electricity is the main energy source.

A feasibility study has been performed for a BEJF factory at Jämtkraft's CHP facility for CHP in Östersund, Sweden. The aim was to assess the feasibility of producing renewable aviation fuel on site by evaluating and comparing different processes, operations, integration options, costs, environmental impacts, business models, and actors. Through this project, a district heating system would reduce peak heat demands during the cold winter months and enable the use of heat from electrofuel production processes to increase energy efficiency.

Reference: (Fagerström et al., 2021)

8.1.8 Proposed: Växjö Energi, Växjö, Sweden

Växjö Energi and some other companies and institutions have been granted financial support by the Swedish Energy Agency to continue their research on the production of sustainable aviation fuel (SAF) in the Växjö region. The funding supports the consortium to continue their study of a first-of-its-kind Fischer-Tropsch SAF production facility that uses forestry residues. This proposed SAF production facility integrates existing bio-based CHP generation and could produce high-quality sustainable fuels and reduce greenhouse gas emissions in the aviation sector. Based on the proposed scheme, the plant could be operational by 2026, with a production of 16 000 tons of SAF annually.

Link:
https://www.veab.se/om-oss/press/pressmeddelanden/2021/projektstart-for-bioflygbransle-av-skogsrester-vid-sandviksverket/

8.1.9 Proposed: Uniper, Sollefteå, Sweden

The German energy company Uniper has signed a letter of intent to investigate the possibility of a production plant for green jet fuel at the Hamre site in Långsele, Sollefteå, Sweden. This would be carried out under SkyFuelH2, an innovative industrial project aiming to establish a unique production facility for sustainable aviation fuel. Sollefteå offers the perfect mix of good access to electricity, biomass, and suitable land areas. By providing the Swedish aviation industry with sustainable fuel to cover up to 10% of its annual fuel needs, SkyFuelH2 would be an important starting point for the transformation of the aviation sector.

Link:
https://www.uniper.energy/sv/sverige/jetfuel

8.1.10 Proposed: Vattenfall and St1, Gothenburg, Sweden

Vattenfall and St1 have signed a letter of intent to develop a fossil-free value chain to produce a synthetic electrofuel; the next step is to jointly conduct a feasibility study. The study will cover the entire value chain for producing the electrofuel from offshore wind, starting in 2029 and gradually expanding towards the target of one million cubic metres annually.

The electrofuel is categorised as a SAF since the only inputs to the production process are fossil-free electricity, water, and recycled carbon dioxide. The electricity will be mainly used to produce hydrogen via electrolysis which, together with the carbon dioxide, can be converted into ethanol and then into the aviation electrofuel. The recycled carbon dioxide is captured from a district heating facility and used for electrofuel production; this is called carbon capture utilisation (CCU). When the electrofuel is combusted in aircraft engines, the harnessed carbon dioxide is released into the atmosphere after being utilised a second time.

Link:
https://www.st1.com/vattenfall-and-st1-form-a-new-partnership-to-produce-a-large-volume-of-fossil-free-aviation-electro-fuel-on-the-swedish-west-coast

8.1.11 Proposed: Liquid Wind, Umeå, Sweden

A feasibility study by Liquid Wind in partnership with Umeå Energi has confirmed that there are excellent conditions for establishing Sweden's third electrofuel facility for the maritime sector at the Dåva cogeneration plant in Umeå, Sweden. A partnership has been launched to make the facility a reality. Capturing the carbon dioxide from the Dåva cogeneration plant will allow the city to take another step towards circularity. Establishing the electrofuel production plant could be an important step towards making Umeå climate-neutral by 2030. All the documents required for an investment decision are planned to be ready in 2024, with the expected start of electrofuel production in 2026.

Link:
https://www.liquidwind.se/news/liquidwind-plans-for-third-electrofuel-facility-in-swedish-umea

8.1.12 Proposed: Aalborg Forsyning, Aalborg, Denmark

Reno-Nord and Aalborg Forsyning have entered into a cooperation agreement to establish one of the world's first commercial Power-to-X facilities in Aalborg. The facility will produce green methanol from captured carbon dioxide from waste incineration and green electricity. The plant will annually recycle 180 000 tonnes of carbon dioxide from waste incineration. Expected to be completed in 2028, the facility will have a 300-400 MW electrolyser plant that converts green electricity into hydrogen, which, combined with carbon dioxide, is converted into methanol. The plant will produce 130 000 tonnes of methanol per year. The Power-to-X plant will also generate excess heat, which will be used in Aalborg Forsyning's district heating network. The plant will recycle 130 GWh of heat annually, corresponding to 7% of the heat consumption of the Aalborg municipality or equal to the heat demand of 5 000 households.

Link:
https://aalborgforsyning.dk/privat/nyheder-og-presse/seneste-nyheder/6-december-2021-power-to-x-anlaeg-i-aalborg-skal-indfange-co2-og-bruge-det-til-gront-braendstof/

8.2 HYDROGEN GENERATION PROVIDING EXCESS HEAT

Investigations have determined that the production and storage of hydrogen for electricity generation is economically challenging. The primary reasons are the associated costs and the heat losses from the two energy conversion steps. However, these heat losses can be recycled, which can create revenue from existing district heating systems.

During the production of green hydrogen, oxygen is produced as a by-product. This oxygen can be used in biomass or waste combustion to improve the burning process and limit the content of nitrogen oxides in the exhaust gases. Additionally, this facilitates carbon capture. Hydrogen can be utilised as a fuel for heavy lorries and in various industrial processes, offering greater flexibility for plant owners and reducing the need for large-scale storage solutions.

The production of hydrogen from weather-dependent electricity sources, such as wind, can play an important role in stabilising the electricity grid. During periods of high grid demand, the electrolysis process can reduce electricity consumption, creating opportunities for businesses that lack the same flexibility. Local battery storage can also contribute to stabilising power fluctuations and provide additional system services.

According to the Global Hydrogen Review (IEA-Hydrogen, 2022), low-emission hydrogen production could reach 16-24 million tonnes per year by 2030 if all the projects currently in progress are realised. This production would comprise of 9-14 million tonnes from electrolysis and 7-10 million tonnes from fossil fuels with carbon capture, utilisation, and storage (CCUS). Achieving these goals would require an installed electrolyser capacity of 134-240 GW by 2030. The production of low-emission hydrogen relies on electrolysis processes powered by low-emission electricity. Currently, the manufacturing capacity of electrolysis systems is approximately 8 GW per year.

There are specific projects, particularly in northern Europe, that aim to generate hydrogen while utilising the excess heat for district heating purposes. Some of these projects are presented as cases below.

References: (IEA, 2022b) and (IEA, 2022c)

Links:
https://www.ri.se/en/what-we-do/projects/system-perspective-of-hydrogen-production-in-connection-to-district-heating
https://www.ri.se/sites/default/files/2023-08/HyCoGen%20Slutrapport%20Produktion%20av%20v%C3%A4tgas%20med%20sektorkoppling%20till%20fj%C3%A4rrv%C3%A4rme.pdf
https://www.ri.se/sites/default/files/2023-07/HyCoGen%20Studie%20hur%20restv%C3%A4rmen%20fr%C3%A5n%20v%C3%A4tgasproduktion%20kan%20bidra%20till%20fj%C3%A4rrv%C3%A4rme_0.pdf

8.2.1 2023: Ovako, Hofors, Sweden

Ovako has started a collaboration to invest in hydrogen production in Hofors, Sweden. The aim is to build Sweden's largest fossil-free hydrogen facility to reduce carbon dioxide emissions, develop local industrial hydrogen production, and take the first step towards developing hydrogen infrastructure for the transport sector. The electrolyser to produce fossil-free hydrogen was completed and inaugurated for operation in September 2023. The 20 MW electricity plant generates eight tonnes of fossil-free hydrogen per day. This hydrogen plant makes Ovako the first company in the world to heat steel with hydrogen prior to steel rolling. The excess heat will be utilised in the local district heating network in Hofors, which is operated by Adven.

This technical solution involves high-temperature processes in steel production with fossil-free hydrogen and oxygen, thus replacing fossil fuels. With the greater need for oxygen than hydrogen in the steel industry, there are also good opportunities for the cost-effective, large-scale use of hydrogen in other areas, such as fossil-free freights with fuel-cell lorries. Overall, this solution offers higher flexibility, improved electricity grid stability, and the possibility to use a higher proportion of renewable energy sources.

Links:
https://www.ovako.com/en/newsevents/news--press-releases/ovako-press-release-detail/?releaseId=B4ADD5355036AA5F
https://www.ovako.com/en/newsevents/stories/hydrogen-plant-ramping-up/
https://ovako-en.newsroom.cision.com/releasedetail.html?swedish-prime-minister-inaugurates-the-world-s-first-plant-to-produce-fossil-free-hydrogen-for-heating-steel-before-rolling&releaseIdentifier=43A02B2C02BD7C08
https://www.nyteknik.se/energi/ovako-tar-sveriges-storsta-elektrolysanlaggning-i-drift/4189049

https://www.energi.se/artiklar/2023/oktober-2023/ovakos-vatgasanlaggning-bidrar-till-fjarrvarmen-i-hofors/
https://adven.com/se/samarbetsberattelser/40-arigt-partnerskap-med-ovako-forgylls-med-hallbar-satsning/

8.2.2 Planned: Hamburg Green Hydrogen Hub, Hamburg, Germany

Shell, Mitsubishi Heavy Industries, Hamburger Energiewerke, and Vattenfall plan to establish the Hamburg Green Hydrogen Hub at the Hamburg-Moorburg power plant site. This hub will convert wind and solar electricity into green hydrogen. The plan is to build an electrolyser with a capacity of 100 MW with potential for further expansion. The hydrogen will be supplied to industry, the port, and various applications in transport in Hamburg and the surrounding area. If all permits are granted on time, hydrogen production can start in 2026.

Hamburger Energiewerke is a municipal company that supplies around 500 000 residential units in Hamburg with local district heating for space heating and hot water. By 2030, the company intends to replace the heat generated from coal combustion with excess heat from alternative sources such as industries, sewage water, waste recycling, and electrolysers.

Link:
https://www.hghh.eu/en

8.2.3 Planned: Shell Hydrogen I, Rotterdam, the Netherlands

Two Shell subsidiaries have made the final investment decision to build Holland Hydrogen I, which will be Europe's largest renewable hydrogen plant once it becomes operational in 2025. The 200 MW electrolyser will be constructed in the port of Rotterdam, where it will produce up to 60 000 kg of renewable hydrogen daily. The renewable power for the electrolyser will come from offshore wind farms.

This project has received a grant from the EU Innovation Fund; see Sub-section 10.6.5 for further information.

Links:
https://www.shell.com/media/news-and-media-releases/2022/shell-to-start-building-europes-largest-renewable-hydrogen-plant.html
https://climate.ec.europa.eu/system/files/2022-12/if_pf_2022_hh_en.pdf

8.2.4 Planned: Everfuel, Holsterbro, Denmark

Everfuel plans to build a hydrogen hub in Holstebro, to support the regional energy transition and accelerate the scale-up of green hydrogen. The hub will be developed in two phases to establish a safe, reliable, and efficient local supply of clean energy. When completed, the hub will significantly reduce the municipality's carbon dioxide emissions by feeding carbon-free hydrogen into a large share of the municipality's activities.

In phase two of the project, Everfuel intends to build a 100 MW electrolyser, a hydrogen terminal, a distribution centre, and a hydrogen refuelling station. The development is planned to commence in 2025. The green hydrogen produced in this phase will phase out fossil fuels by replacing natural gas in selected industrial processes. Excess heating from the hydrogen production facility is planned to be fed into the local district heating network.

Link:
https://news.cision.com/everfuel-a-s/r/everfuel-launches-plan-for-holstebro-hub-to-scale-green-hydrogen-for-industry-and-mobility,c3619050

8.2.5 Planned: Vuosaari Hydrogen hub, Helsinki, Finland

The Helen company has chosen Sweco to cover the basic engineering of the Helsinki Hydrogen Hub (3H2) project in Vuosaari, Finland. With this pilot project, Helen intends to create the necessary capabilities for large-scale Power-to-X production. The project aims to reduce carbon dioxide emissions in transport and district heat production by up to 70 000 tonnes over the plant's 20-year lifecycle. 3H2 is the first project of its kind, combining zero carbon emissions with the four uses of hydrogen: electricity, transport, heating, and energy storage. One key feature of the plant is its capability to convert the hydrogen back into electricity with a fuel cell (Power-to-H2-to-Power) to balance the electricity grid. All excess heat generated by the hydrogen production process will be recovered and utilised via a heat pump in Helen's district heating network, raising the efficiency of the plant to almost 90%.

Green, emission-free hydrogen is produced in an electrolyser using water and electricity. The hydrogen can be used as a transport fuel, heat, electricity, or for energy storage to balance fluctuations in electricity production and demand peaks caused by weather conditions. Green hydrogen and carbon dioxide can also be used to produce synthetic e-fuels, such as e-methane or e-methanol, for example, by utilising carbon dioxide emissions from a nearby industrial area.

Link:
https://www.helen.fi/en/news/2022/helens-first-hydrogen-plant-is-designed-by-sweco

8.2.6 Proposed: Everfuel and Karlstads Energi, Karlstad, Sweden

Everfuel has signed a memorandum of understanding with Karlstads Energi to collaborate on developing a hydrogen hub in Karlstad. The two parties plan to explore the commercial and technical feasibility of constructing a 20 MW electrolyser as the first phase of the hub development. The facility will produce green hydrogen, supply excess heat to the local district heating network owned and operated by Karlstads Energi, utilise the produced oxygen for industrial purposes, and supply green fuel to mobility and industry partners. Everfuel and Karlstads Energi aim to further develop the hub including expanding the electrolyser’s capacity by 100 MW during the second phase of the project. The first phase is expected to end in 2025, depending on funding and permissions.

Links:
https://news.cision.com/everfuel-a-s/r/everfuel-signs-mou-with-karlstads-energi-for-establishing-a-hydrogen-hub,c3620798

https://www.energi.se/artiklar/2022/maj-2022/darfor-siktar-karlstads-energi-pa-vatgasproduktion

8.2.7 Proposed: CIP Høst project, Esbjerg, Denmark

Copenhagen Infrastructure Partners (CIP) is managing a project called HØST PtX Esbjerg to use excess heat from the production of hydrogen and ammonia for district heating applications. As part of the project, an ammonia plant is being developed for the GW-scale use of electrolysis, making it the first ammonia plant at this scale in Europe. The plant will convert renewable electricity, primarily sourced from wind and solar, into hydrogen and store it as ammonia. Ammonia is produced by reacting nitrogen with hydrogen under a high temperature and pressure. Effectively, this is a kind of Power-to-X (PtX) energy storage technology.

Green ammonia can be used as feedstock for fertiliser production and as a green fuel in the maritime industry. Thus, the project will pave the way for decarbonising hard-to-abate sectors such as shipping, agriculture, and industry. The annual expected electricity consumption is 5 TWh for the 1000 MW electrolyser, which will produce approximately 600 000 tonnes of ammonia. The current plan includes a final investment decision in 2025 followed by commissioning in 2029.

Excess heat from the plant will be used for district heating in Esbjerg, which has around 15 000 households through the distoi9ct heating network operated by DIN Forsyning. This will reduce the carbon footprint of the local district heating company. The current annual heat delivery to customers in the municipalities of Varde and Esbjerg is about 1000 GWh, previously supplied from waste incineration and a coal-based CHP.

Links:
https://hoestptxesbjerg.dk
https://hoestptxesbjerg.dk/about-ptx/

8.3 HYDROGEN USAGE IN CHP PLANTS

Hydrogen and hydrogen-based fuels are emerging as promising alternatives to carbon-based fuels, offering a zero- or low-carbon solution. Hydrogen can be produced by utilising water and electricity. It can be stored for months and used across industries and applications. When hydrogen is burned, it generates thermal energy and only emitting water vapour, making it a clean fuel. By using hydrogen in power generation assets like gas turbines or CHP units, useful electricity and heat can be generated with zero-carbon emissions. With the necessary modifications to gas turbines and the establishment of a reliable hydrogen supply chain, hydrogen could significantly reduce the use of fossil fuels.

In most current projects, the power-to-hydrogen-to-power concept is applied, wherein surplus electricity, primarily from intermittent renewable sources, is utilised in electrolysers to produce hydrogen. The key advantage is that hydrogen can be stored more easily than electricity itself. In some cases, battery storage is incorporated to optimise the overall system performance. When needed, hydrogen then serves as the energy source for operating power-only or CHP plants. The recycled heat can be fed into a district heating system, providing green heat to customers.

Reference: (Koeppe et al., 2022)

8.3.1 2020: APEX Energy, Teterow, Germany

This hydrogen CHP case study is based in northern Germany. APEX Energy Teterow GmbH, a leading green hydrogen production and storage system developer, operates a hydrogen power centre at its headquarters in Rostock-Laage. Inaugurated in 2020, the hydrogen plant incorporates a small 115-kW hydrogen CHP system with 1 MW of battery storage. The system generates electricity and heat for use at the manufacturing plant and in the office buildings. It can be operated with up to 100% green hydrogen produced on site from renewable energy using a McPhy electrolyser that can generate up to 300 ton per year. The hydrogen is stored in an APEX storage system and there is a fuel cell with 100 kW of electrical power. In addition to its use in CHP, the hydrogen produced at the power centre is also made available at a public hydrogen filling station on the factory premises, which can supply up to 40 buses and 200 cars.

Link:
https://www.districtenergy-digital.org/districtenergy/library/item/autumn_2021/3950841/

8.3.2 2021: Siemens, Finspång, Sweden

The Zero Emissions Hydrogen Turbine Centre has been operational in Finspång since spring 2021. The aim is to show how hydrogen, gas turbines, renewable energy generation, and energy storage work together in a flexible and sustainable energy system. At the gas turbine manufacturing plant, there is a test centre where the gas turbines are tested before they are delivered to customers. The test fuels are mainly natural gas and biogas. During the test, the turbines generate a large amount of electricity. This is fed into the national electrical grid, however, there is always some excess electricity that cannot be utilised.

This facility is the core of the demonstration plant. Solar panels have been installed to produce electricity from a renewable but volatile source. A small electrolyser has also been installed to produce green hydrogen from solar energy. The hydrogen is stored and then fed into the test centre as the fuel for turbine testing. With a nominal power output of 225 kW, up to 5.4 MWh of electrical energy can be converted into 4 MWh of hydrogen per day. This is equivalent to about 100 kg of hydrogen per day.

Batteries have been installed to increase the flexibility of the zero-emission energy system. The plant reduces the carbon dioxide footprint of the gas turbine facility and the local community. It also supports Siemens Energy’s target to run gas turbines on 100% hydrogen by 2030.

Link:
https://www.zehtc.org/

8.3.3 2021: Clemson University, Clemson, USA

In early 2021, Clemson University, Duke Energy, and Siemens Energy teamed up to research the use of green hydrogen for energy storage and as a low or zero-carbon fuel source for a CHP plant. Siemens Energy was awarded $200 000 from the U.S. Department of Energy for the demonstration research project H2-Orange, which aims to evaluate hydrogen production, storage and co-firing with natural gas. The team studied the use of Siemens Energy's Silyzer electrolyser technology to produce hydrogen to help power a natural gas turbine at the Duke Energy Clemson CHP plant. The Silyzer can use electricity from sources including solar, wind, nuclear, and hydro to produce hydrogen without carbon emissions. Duke Energy aims to cut its carbon emissions by 50% by 2030 and become carbon neutral by 2050.

Link:
https://www.districtenergy-digital.org/districtenergy/library/page/fall_2022/25/

8.3.4 2022: Wien Energie, Vienna, Austria

The energy company Wien Energie and a group of partners will investigate the blending of hydrogen with natural gas to generate power at a large CHP plant in Vienna. As part of the pilot project, one of Austria's largest gas turbines at the Donaustadt CHP plant is being converted to run partly on hydrogen. The upgrade was completed in 2022 and the plant's capacity was raised by about 23 MW. Currently, The Donaustadt CHP plant can produce 350 MW of heat and up to 395 MW of electricity.

Recently, the partners prepared the necessary infrastructure to test using 15% hydrogen in the fuel for the gas turbine in the summer of 2023. Then, the hydrogen percentage in the fuel was planned to be doubled. The first test results was expected to become available at the end of 2023. The use of just 15% green hydrogen in the fuel would allow the Donaustadt CHP plant to reduce its carbon dioxide emissions by about 33 000 tonnes per year.

Link:
https://renewablesnow.com/news/austrias-wien-energie-to-test-running-chp-plant-partly-on-hydrogen-791007/

8.3.5 2022: Engie, Saillat sur Vienne, France

A consortium of European companies, research institutes, and universities have launched a fully integrated power-to-hydrogen-to-power project at the industrial scale in an existing real-world power plant. The four-year project to demonstrate HYFLEXPOWER is converting a 12 MW_e CHP plant at Engie Solutions' Smurfit Kappa pulp-and-paper industrial site in Saillat-sur-Vienne, France, to demonstrate the power-to-hydrogen-to-power cycle. Siemens Energy which plays the crucial role of project coordinator for the HYFLEXPOWER pilot, provides the electrolyser system to produce hydrogen from surplus renewable electricity in the region. Part of the produced hydrogen is stored for later use. Siemens is upgrading the existing SGT-400 industrial gas turbine at the CHP plant to burn a variety of natural gas and hydrogen mixes for power generation, working to gradually increase the hydrogen percentage in the fuel to at least 80%, and eventually to 100%. Meanwhile, Engie will build the hydrogen production and storage facility, including the natural gas and hydrogen mixing station.

Links:
https://www.powermag.com/worlds-first-integrated-hydrogen-power-to-power-demonstration-launched/
https://press.siemens.com/global/en/pressrelease/hyflexpower-worlds-first-integrated-power-x-power-hydrogen-gas-turbine-demonstrator
https://press.siemens-energy.com/global/en/pressrelease/first-tests-power-hydrogen-power-hyflexpower-demonstrator-successfully-completed

8.3.6 2023: Caterpillar, St Paul, USA

Caterpillar is working on a three-year project with Minnesota-based District Energy St. Paul to demonstrate a hydrogen-based CHP system. The project is supported and partially funded by the U.S. Department of Energy and is backed by the National Renewable Energy Laboratory. This hydrogen demonstration project will enable the evaluation of additional hydrogen fuel options for an existing energy-efficient engine, providing even more possibilities for helping customers meet their climate-related objectives. To assess the potential of a hydrogen-fuelled CHP system under real-world operating conditions, power and heat from the demonstration project will be integrated into District Energy St. Paul's electrical and thermal infrastructure. District Energy St. Paul distributes hot and chilled water to cool and heat buildings and single-family homes.

Link:
https://www.caterpillar.com/en/news/corporate-press-releases/h/caterpillar-to-launch-demonstration-project-using-hydrogen-fueled-heat-power-system.html

8.3.7 Planned: Vaasan Sähkö, Vaasa, Finland

In the Finnish city of Vaasa, plans are underway to build a facility that will produce hydrogen for the electricity market. The electrolysis process uses electricity to produce hydrogen from water. The hydrogen is then stored in tanks under high pressure. When the gas is to be used, it is taken out of the tank and burned in diesel engines. Thus, the technology uses a power-to-X-to-power cycle. The idea is that electricity from wind power is harnessed in the form of hydrogen and then transformed back into electricity. The district heating system in Vaasa can benefit from the excess heat generated by the process. The project is a collaboration between Wärtsilä, Vaasan Sähkö, the energy company EPV, and the city of Vaasa. The diesel engine is expected to be put into operation by 2026 at the latest.

Links:
https://www.wartsila.com/media/news/15-01-2021-wartsila-plus-venture-partners-in-vaasa-to-cooperate-in-wind-power-to-hydrogen-to-electricity-project-2845339
https://svenska.yle.fi/a/7-10027840

8.3.8 Proposed: Ryaverket, Gothenburg, Sweden

The natural gas-powered Ryaverket CHP plant in the Swedish city of Gothenburg is being analysed for a gradual switch to more renewable fuels. The goal of the proposed scheme is for all district heating in Gothenburg to be produced from renewable or recycled energy sources by 2025. Together with Siemens Energy, Göteborg Energi will investigate whether it is possible to use other green fuels, such as liquid biodiesel, in the facilities. In the long term, Göteborg Energi is also considering adding hydrogen to the fuel mix.

Link:
https://www.energi.se/artiklar/rya-kraftvarmeverk-testar-nya-branslen-i-gasturbinerna/

8.4 PETROCHEMICAL PLANTS

A petrochemical plant is a facility for processing feedstocks traditionally derived from petroleum products. A petrochemical complex hosts a sequence of reactions and separation procedures that involve different temperatures and pressures, making the overall process energy intensive. Chemical production involves numerous processes that include various heating, cooling, and condensation stages. Consequently, heat exchangers find wide-ranging applications in this industry. This indicates that there is considerable potential for recuperating and reusing heat in petrochemical plants.

Excess heat recovery in petrochemical plants is common and contributes to increased energy efficiency. However, the process of decomposition of oil and gas molecules also results in carbon dioxide emission. To achieve more climate-neutral solutions, petrochemical plants are exploring the possibilities to switch their input from fossil fuel-based feedstock to renewable sources like biomass. This fuel transition, along with recovering heat for district heating, can significantly reduce carbon dioxide emissions in this industry.

Reference: (Liu et al., 2022)

Link:
https://www.energi.se/artiklar/2023/september-2023/darfor-driver-den-okade-plastanvandningen-pa-oljeindustrin/

8.4.1 Proposed: Borealis - biomass, Stenungsund, Sweden

In its facility in Stenungsund, Borealis is exploring a plastic production process that uses renewable raw materials instead of conventional oil and natural gas as feedstock. Suitable raw materials include agricultural by-products that would otherwise go to waste. In a cracker facility, the raw materials undergo heating, causing the breakdown of large molecules into smaller ones. This process yields hydrocarbons such as ethylene and propylene, which are subsequently employed in the production of plastic goods. The excess heat generated throughout the process is planned to be harnessed for district heating.

Link:

https://www.nyteknik.se/nyheter/forsta-testerna-tillverka-plastravara-av-jordbruksrester/659806

8.4.2 Proposed: Borealis – chemical recycling, Stenungsund, Sweden

Currently, a significant amount of plastic waste is incinerated because it cannot be mechanically recycled. Borealis is exploring the feasibility of building a chemical recycling facility in Stenungsund, which would be the first in Sweden. One option for chemical plastic recycling is pyrolysis, which converts plastic into a chemical feedstock that can then be used to manufacture virgin-quality polymers. Using the heat generated during the process for district heating purposes can increase the overall energy efficiency.

Reference: (Jeswani et al., 2021)

Link:
https://www.nyteknik.se/nyheter/har-ska-plast-atervinnas-pa-kemisk-vag/334653

8.5 ELECTRIC TRANSFORMERS

The electrical energy wasted in electrical grids in the form of heat can be viewed as a heat source. The electrical substation is one of the parts of an electricity generation, transmission, and distribution system that is subject to heat recovery. Typically, transformers in electrical substations generate excess heat ranging from 20 to 70°C, so heat upgrades using heat pumps are often needed.

Transformers have two types of losses: load loss and no-load loss. Load loss is caused by the resistance of the windings, which increases proportionally with the square of the electrical current. No-load loss results from hysteresis losses and eddy current losses, which occur when the transformer is energised but no power is delivered. While load losses fluctuate based on the power drawn from the transformer, no-load losses remain constant. The percentage of load and no-load losses can vary across transformers. However, the average heat loss from transformers is estimated to amount to 0.5% of the load. Transformers with larger capacities, for example, those exceeding 60 MVA, are particularly relevant for heat recovery and reuse.

To recover heat from transformers, the heat recovery system is needed to be connected to the existing cooling system. Transformers typically use oil as the internal cooling medium, which circulates through the core naturally or with the assistance of pumps. The heat carried by the oil is then transferred to an external medium, such as the surrounding air or water, using a heat exchanger. If the target heat application is district heating, a heat pump is often required to increase the temperature.

References: (Dorotić et al., 2022) and (Davies et al., 2023).

8.5.1 2023: Svenska Kraftnät, Stockholm, Sweden

Svenska Kraftnät and Stockholm Exergi are enhancing grid efficiency through heat recovery at a new electricity substation. This will be done under the Skanstull substation project, which was supposed to go online in 2023. The substation was built with an integrated cooling and heat recovery system. The substation can provide up to 1 000 MW of electricity. While the power transformer has a limited heat loss, Stockholm Exergi expects to recover nearly 8 GWh annually and reuse this heat in its district heating network. Once the heat recovery system is fully operational, the recovered heat will be enough to heat 2 200 modern residential flats. To allow the heat supplier to make the necessary investments, Stockholm Exergi purchases the heat from the owner of the excess heat, making the transaction a win-win for both parties.

Link:
https://stockholmdataparks.com/2021/04/23/swedish-tso-svenska-kraftnat-deploys-heat-recovery-at-new-power-substation/

8.5.2 Proposed: A2A, Milan, Italy

The energy company A2A presented a demonstration project for the REWARDHeat project, which aimed to explore a new generation of low-temperature district heating and cooling networks that can recover renewable and excess heat available at low temperatures. The demonstrations in Milan comprised two pilot sites in Viale Gadio and Via Balilla. Two small-scale district heating and cooling networks was intended to operate at neutral temperatures and integrate the use of excess heat.

The demonstration project in Viale Gadio consisted of a newly built low-temperature district heating network designed to exploit the excess heat from an electric transformer. This excess heat is currently dissipated into the air through dry coolers and an oil circuit. The heat, which is available at 30-40°C throughout the year, was planned to be the main heat source for space heating in the municipal aquarium and the electrical cabinet. The excess heat was planned to be collected using a heat pump. However, this proposal never reached an investment decision since the client refused the project proposal.

Link:
https://www.rewardheat.eu/en/Demonstration-Networks/Milan

8.6 NEW INDUSTRIAL PROCESSES

The recovered heat from industrial excess heat can be utilised internally in the same industry or externally in other applications. Recovering industrial excess heat for district heating, particularly for low-temperature systems, can enhance both the efficiency of the industrial sector and the supply of district heating. The primary issue lies in effectively transporting the heat from its point of generation to the distribution network. The cost-effectiveness of utilising industrial excess heat for district heating relies heavily on the proximity of industrial sites to district heating networks. This is because of the increased expenses associated with heat losses and the investment in pipeline construction as the distance grows.

Historically, energy-intensive sectors like petrochemical plants, oil refineries, and cement plants have been the focus of heat recovery initiatives. However, in recent years, the idea of reusing excess heat has expanded to encompass new industrial processes. The food production industry serves as an illustrative example, where several European projects have been devised to harness excess heat. These projects include coffee roasteries, vegetable protein production facilities, and algae production sites. The consistent production pattern of excess heat is a significant advantage that new industries, such as food and building material industries, offer for district heating applications. The key consideration is that the industrial plant must remain operational for a sufficient duration to recoup the investment cost associated with expanding the district heating system.

References: (Jodeiri et al., 2022), (Atienza-Márquez et al., 2019), (Fang et al., 2013)

8.6.1 2019: Hamlet Protein, Horsens, Denmark

In 2019, Fjernvarme Horsens and Hamlet Protein entered into an agreement to utilise the excess heat generated by the latter, which is in the order of 70 GWh per year. This amount of excess heat from Hamlet Protein provides district heating for 3 300 households in Horsens. As the district heating network is expanded in the coming years, the amount of recovered excess heat may increase.

Link:
https://fjernvarmehorsens.dk/nyheder/pressemeddelelse-21-marts-2019.php

8.6.2 2020: Paulig and Helen, Vuosaari, Finland

The Paulig coffee roastery, located in the Vuosaari (Nordsjö) district east of Helsinki, recovers its excess heat to provide thermal energy for the residential sector in Helsinki. This pilot project received the 2020 Energy Genius prize, which was granted by Finland's Ministry of Economic Affairs and Employment, the Finnish Energy Authority, and the governmental sustainable development company Motiva.

Paulig, a family-owned food and beverage company, uses renewable energy sources and roasts all its coffee using biogas. The company has significantly improved the energy efficiency of its roasting coffee lines, resulting some of excess heat becoming available. With the help of a heat recovery system, heat is recovered from the roasting process. The recovered heat is primarily utilised for the company's own heating. The excess heat that is not used on site is fed into the district heating network by the heat supply company Helen, whose district heating network covers most of Helsinki. Helen takes advantage of its status as an open district heating operator able to both buy and sell heat in the market. It is estimated that the excess heat from Paulig could be enough to satisfy the annual heat demand of 1000 two-room flats, and it will continue to increase in the future when Paulig will increase their activities.

Links:
https://www.helen.fi/en/news/2020/energy-genius
https://www.pauliggroup.com/taste-the-change/five-acts-of-sustainability-during-the-past-decade

8.6.3 2022: AstraReal, Gustavsberg, Sweden

Since late 2022, excess heat from AstraReal's algae cultivation has been used to deliver district heating to over 2 500 flats in Gustavsberg. AstraReal's manufacturing process is energy-intensive and requires both electricity and cooling. Using the excess heat for heating homes and premises, the residents of Gustavsberg now have more than 20% of their heating needs met by recycled heat. The heat recovery facility efficiently recovers excess heat from the manufacturing process, providing over 15 GWh of heat annually that is reused in the local district heating network operated by Vattenfall.

Link:
https://news.cision.com/se/vattenfall/r/nu-varmer-algodling-over-2500-lagenheter-i-gustavsberg,c3654460

8.6.4 Planned: Mycorena, Falkenberg, Sweden

Mycorena and Falkenbergsgruppen plan to run a joint project to establish a facility for the large-scale production of mushroom-based protein in Falkenberg. The excess heat from the facility will be recycled into the district heating system in Falkenberg. The commissioning was planned for 2022, but was later delayed to 2025.

Links:
https://www.mynewsdesk.com/se/guventures/pressreleases/den-foersta-anlaeggningen-foer-mykoproteinproduktion-ska-byggas-i-falkenberg-aat-mycorena-3095937
https://www.hn.se/hallands-aff%C3%A4rer/etablering-av-mycorenas-fabrik-i-falkenberg-ytterligare-f%C3%B6rsenad-1.111723727

8.6.5 Planned: HYBRIT, Gällivare, Sweden

Gällivare Energi has received close to SEK 10 million in project funding to develop a more sustainable district heating system that uses excess heat from a new industry process. A part of the planned scheme is the investment that the mining company LKAB will make in producing fossil-free steel through the new HYBRIT technology. The ultimate goal is to prepare for a 100% circular and climate-smart district heating system in Gällivare, Sweden.

This project has received a grant from the EU Innovation Fund; see Sub-section 10.6.5 for further information.

Links:
https://gallivare.se/arkiv/nyheter/2023/2023-04-14-eu-stod-till-gallivare-nar-industrins-restvarme-ska-bli-fjarrvarme
https://www.fvb.se/fvb-nytt/spill-fran-jarnsvamp-ska-varma-gallivare/

8.6.6 Planned: Fertiberia, Luleå, Sweden

Fertiberia has signed a memorandum of understanding with the Region of Norrbotten, Sweden, to develop the world's first 100% green and emission-free ammonia and fertiliser production site by 2026. Based on electrolyser technology, the site will only use water and air as raw materials. It will be supplied with renewable energy from wind and hydropower sources. With more than 600 MW of electrolysers, the new site in Luleå will be innovative in its design and development. The production capacity of green ammonia will be 1 500 tonnes per day. The electrolysers will generate heat losses that can be recycled into district heating.

Link:
https://www.grupofertiberia.com/media/605649/20211015-np-planta-fertiberia-suecia_def_en-1.pdf

8.6.7 Planned: Yara, Sluiskil, the Netherlands

Yara and Ørsted have joined forces to develop a 100 MW wind-powered electrolyser plant for renewable hydrogen production. Located at Yara's plant in the Dutch city of Sluiskil, the new plant aims to replace fossil-based hydrogen with renewable hydrogen for ammonia production. The renewable hydrogen would generate around 75 000 tonnes of green ammonia annually and potentially abate more than 100 000 tonnes of carbon dioxide emissions per year. The green ammonia is intended to be used for producing carbon-neutral fertilisers and decarbonising the food value chain. It also has potential as a climate-neutral shipping fuel. The electrolysers will generate heat losses that can be recycled into a district heating network.

Link:
https://www.yara.com/corporate-releases/orsted-and-yara-seek-to-develop-groundbreaking-green-ammonia-project-in-the-netherlands/

8.7 COMBINED HEATING AND COOLING WITH CENTRALISED DISTRICT COOLING

In combined heating and cooling systems, one way to enhance energy efficiency is to transfer the heat generated during the cooling process to the district heating network. This is typically accomplished through the integration of heat pumps in the system. The aim is to harness the synergy benefits of combined heating and cooling by simultaneously utilising both ends of a heat pump or by operating a heat pump and a chiller separately. This approach enables the utilisation of excess heat from the cooling process to meet heat demands and the excess cold from the heating process to meet cooling needs.

For the simultaneous use of excess heat and cold in combined systems, the heating and cooling demands must occur at the same time, with the cooling demands being somewhat lower than heating demands. Seasonal heat and cold storages can be employed to overcome this balancing challenge. During the winter, the cold generated by heat pumps can be stored for later use in the summer, while the low-temperature heat generated by the chiller in the summer can be stored for utilisation in the winter. This annual cycle of storing both heat and cold can be facilitated through by using large centralised low-temperature aquifer or borehole thermal energy storage systems. Adding these thermal storage units facilitates the integration of a district heating and cooling system into a smart energy system and allows for greater flexibility in utilising variable renewable energy sources.

The combined heating and cooling synergy can be achieved using either centralised or decentralised cold supply approaches. In a centralised system, the distribution of heat and cold is achieved through separate district heating and district cooling networks. Centralised cooling systems are more suitable for incorporating seasonal storage due to the cost advantages associated with the economies of scale of large thermal energy storage solutions.

Reference: (Østergaard et al., 2022)

8.7.1 1989: Oslofjord Varme, Sandvika, Norway

During the 1980s, when there was a need to provide sufficient energy for emerging developments in the Sandvika area, it was determined that district heating generated by large heat pumps was the most cost-effective solution. The intended heat source was the wastewater from a recently constructed sewage tunnel.

Recognising that a heat pump has both a warm and a cold side, it was recognised that the cold side could be used for district cooling. The initial plant with two heat pump units was built in 1989 with 13 MW of heat and 9 MW of cold. As more customers joined the network, the need for cooling steadily increased. The plant was extended in 2008 with a third heat pump with 7.7 MW of heat and 5.2 MW cold in winter mode, increasing the total capacity to 21 MW heat and 14 MW cold.

The network configuration for this case is presented in case 4.6.1.

Links:
https://www.oslofjordvarme.no/anlegg/sandvika/
https://www.friotherm.com/wp-content/uploads/2017/11/sandvika_e005_uk.pdf
https://etkhpcorderapi.extweb.sp.se/api/file/1138

8.7.2 1995: Stockholm Exergy, Stockholm, Sweden

As mentioned in Sub-section 4.6.2, the Swedish capital of Stockholm has the most extensive district cooling system in Europe with respect to trench length. Initiated in 1995, it is now 250 km long and is still under development. By developing and modernising district cooling in the city, Stockholm Exergi now offers a more elaborated and safer district cooling service.

Stockholm Exergi manages a large district cooling network which has an annual cold delivery of about 450 GWh for a design cold load of 220 MW. The district cooling is obtained from heat pumps and free cooling through seawater. In 2020, 50% of the cold generated for district cooling was derived from large heat pumps. Part of the heat generated in the cooling process is used by heat pumps to supply district heating. The main supply sources of district heating are waste incineration, biomass CHPs, and centralised heat pumps that use recycled heat from sewage treatment facilities, district cooling, and seawater.

Reference: (Levihn, 2017)

Link:
https://www.stockholmexergi.se/en/district-cooling/

8.7.3 2006: Helen, Helsinki, Finland

As earlier described in Sub-section 0, the energy company Helen has been operating the Katri Vala site in Helsinki since 2006 with some large heat pump for exploitation of the combined heating and cooling synergy. Excess heat from buildings is gathered through district cooling and fed into the district heating system. This creates an integrated energy ecosystem where a minimal amount of heat is wasted. Heat pumps are responsible for meeting a large part (around 90%) of the district cooling demand. The generated heat is used in the district heating supply. CHP generation, district cooling, and district heating complement each other perfectly in this integrated system.

The network configuration for this case is presented in case 4.6.3.

Link:
https://www.districtenergyaward.org/combined-heating-and-cooling-in-helsinki/

8.7.4 2015: Stanford University, Stanford, USA

As previously described in case 4.6.4, the Stanford Energy System Innovations (SESI) project delivered a major transformation of the university's campus district energy system. The transformation replaced gas-fired CHP and steam distribution with electrically-powered combined heating and cooling and hot water distribution. The cooling system was created in the 1960s to meet the cooling needs of the campus buildings.

In 2015, a new water-based district heating system was added, serving 300 buildings. This integration of the cooling, heating, and electricity systems allowed for the integrated optimisation of all systems. SESI was supposed to reduce the campus's greenhouse gas emissions by 68% and decrease its water use by 18%. The heart of SESI was heat recovery, where 57% of the excess heat from the campus's chilled water system (previously discharged out of evaporative cooling towers) was reused to meet 93% of the campus's heating and hot water needs.

References: (Stanford University, 2014), (Stagner, 2016), (de Chalendar et al., 2019), and (Stanford News, 2020)

Link:
https://www.districtenergyaward.org/stanford-university-district-energy-system/

8.7.5 2022: Vattenfall, Berlin, Germany

Since 1997, the cooling centre at Potsdamer Platz in Berlin has reliably supplied around 12 000 offices, 1 000 flats, and numerous institutions with district cooling. Vattenfall and Siemens Energy have started to run a new large, high-temperature heat pump in the cooling centre. This pilot project aims to draw reliable conclusions about the technical and economic potential of heat generation via large-scale, high-temperature heat pumps. The heat produced by this process used to be released into the environment via cooling towers.

Thanks to the integration of a new high-temperature heat pump, heating, cooling, and electricity are combined for enhanced resource efficiency. The new technology makes use of the excess heat, increases the energy efficiency of cold generation, and provides green heat from renewable electricity for this Berlin district. Using the heat pump significantly reduces heat emissions into the environment and provides an additional heat supply for the district heating network of around 55 GWh annually.

Reference: (Huettl, 2022)

Link: https://group.vattenfall.com/press-and-media/pressreleases/2021/berlins-largest-air-conditioning-system-is-gearing-up-to-generate-climate-friendly-heat-in-the-future

8.7.6 2022: Nordhavn, Copenhagen, Denmark

As earlier explained in case 7.8.3, a new energy centre is being built by HOFOR in Nordhavn to provide combined district heating and cooling in the future. The plant will supply district heating to many new homes and offices. At the same time, the centre will supply space-saving air conditioning via district cooling to several companies and hotels. The heat generated in the cooling process is a source of heating. This energy centre was initially commissioned in the end of 2022.

Link: https://www.hofor.dk/pressemeddelse/ny-energicentral-huser-baade-varme-kulde-og-spildevand/

8.8 COMBINED HEATING AND COOLING WITH DECENTRALISED DISTRICT COOLING

As described in the preceding Section 8.7, combined heating and cooling systems can be categorised based on their district cooling networks, which can be centralised or decentralised. In a decentralised cold supply configuration, the distribution of heat and cold occurs through a common network that operates at temperatures close to those in district cooling systems. The cold supply in this setup is generated by decentralised heat pumps primarily used for heating purposes. However, these decentralised heat and cold supplies can be complemented by centralised heat and cold supplies to ensure the balancing of hourly heat and cold demands.

In decentralised combined heating and cooling systems, heat is provided through local heat pumps located at customer substations. These heat pumps extract heat from the warmer pipe and release it at a lower temperature to the colder pipe. Each customer substation can provide heat and cold to an individual building or a cluster of buildings. An important implication is that cooling can be supplied directly from the colder pipe at a suitable temperature.

Reference: (Østergaard et al., 2022)

8.8.1 2013: ETH Hönggerberg, Zürich, Switzerland

The operation of a multi-energy system by using geothermal heat and cold in the Anergy Grid installed at ETH Hönggerberg campus in Zürich has been implemented. In this system, centralised heat and cold generation based on fossil fuels has been replaced by a dynamic underground thermal network connecting geothermal fields, which serve as heat sources and storage, with demand clusters requiring heating and cooling.

The transition is scheduled to be completed by 2026. The ETH buildings will then be heated using multiple decentralised heat pumps integrated with geothermal storage units and an excess heat recovery loop of buildings and laboratories included in the cooling side. Heat and cold are currently distributed through three closed loops of pipes. These loops are designed for carrying warm, cold, and free cooling/excess heat water flows with varying temperatures during the year. The system can reduce the carbon dioxide emissions of the university campus by 72% compared to the current conventional fossil-based centralised heating and cooling system.

Reference: (Gabrielli et al., 2020)

8.8.2 2013: Krokslätts Fabriker, Mölndal, Sweden

The REWARDHeat project aimed to investigate a new generation of low-temperature district heating and cooling networks that can recover renewable and excess heat at low temperatures. The city of Mölndal was a demonstrator city for the project. The Mölndal demonstrator consisted of a newly constructed low-temperature sub-network that uses a borehole seasonal thermal energy storage system which was installed in 2013. A centralised heat pump provides space heating, while a local heat pump provides domestic hot water. The newly constructed district heating and cooling sub-network is linked to the existing district heating network. This new sub-network will supply a complex that includes a historic manufacturing building which has been converted into a contemporary office, two new office buildings, five residential buildings with flats, and one hotel.

Link:
https://www.rewardheat.eu/en/Demonstration-Networks/Helsingborg-and-Molndal

8.8.3 2017: Paris-Saclay University, Paris, France

In 2017, Paris-Saclay University initiated the implementation of a combined heating and cooling system. The district energy network incorporates renewable energy sources, two low-temperature exchange networks, and heat storage units in low-temperature buildings. The energy supply chain consists of seven semi-centralised heat pump stations at the cluster level and natural gas boilers for heat provision. The system also includes two 700-metre geothermal wells that supply heat 25-30°C.

The campus's district energy system features cluster substations that utilise heat pumps to deliver both chilled and hot water to meet the thermal requirements of individual building blocks. Furthermore, these cluster substations are equipped with heat exchangers that capture excess cooling and heating from the buildings. The system's heat and cold capacities are 37 MW and 10 MW, respectively; the annual heat and cold generation is respectively 40 GWh and 10 GWh.

The network configuration for this case is presented in case 4.5.2.

Reference: (Galindo Fernández et al., 2021)

8.8.4 2018: Medicon Village, Lund, Sweden

E.ON ectogrid is a grid initially developed in 2018 to fulfil several functions simultaneously from the same grid: heat and cold distribution, thermal storage, and flexibility. The pipe system consists of two tubes, carrying warm and cold flows which can be pumped in different directions and have varying temperatures over the year. The grid’s low-temperature (0–40°C) maximises the use of excess energy. Every building connected to the E.ON ectogrid has a heat pump and/or a cooling machine that raises or lowers the temperature according to the building’s needs. This means that the water in the grid does not need to be as warm or cold as the target temperature for heating or cooling.

In this energy system, each building sends its excess heat and cold to other buildings to meet their needs. The E.ON ectogrid supplies heat and cold to Medicon Village, located in Lund. It is a research, innovation, and community district where 2 600 people work at more than 170 life-science companies and organisations. The E.ON ectogrid connects 15 commercial properties and residential buildings with different heating and cooling needs. Before the E.ON ectogrid was installed, approximately 10 GWh of district heating and 4 GWh of district cooling were supplied annually. The long-term goal is to balance 11 GWh of the annual demands within the system and only buy 3 GWh of heat from the local district heating system.

The network configuration for this case is presented in case 4.5.3.

Link:
https://www.eon.se/foeretag/integrerade-energiloesningar/ectogrid/ectogrid-medicon-village

8.9 COMBINED HEATING AND COOLING - AIR-COOLED DATA CENTRES

An immense potential for heat recovery lies in harnessing the warm air emitted by data centres. The excess heat in the air can be extracted and fed into local district heating networks. The process of recovering heat from data centres targets the residual heat from the cooling of the equipment housed in server halls. These cooling operations are necessary to maintain the desired operating temperatures of the installed components. The heat generated by the servers, processors, memory chips, and disk drives is significant. In modern data centres, two primary cooling technologies are commonly employed: air cooling and liquid cooling systems. Most of the data centres presently operating in Europe employ air cooling systems known as computer room air conditioners or computer room air handlers, which typically facilitate heat recovery in the temperature range of 25-35°C.

References: (Tsung-Te Lai et al., 2010), (Tepper et al., 2012), (Davies et al., 2016), (Persson et al., 2022), and (Gynther et al., 2022).

8.9.1 2009: Academica, Helsinki, Finland

The energy company Helen recovers and utilises all the excess heat produced at the data centre installed in Helsinki by the IT company Academica. The heat is transferred onwards from the data centre with the aid of heat pumps and is used to heat the homes of Helsinki residents in a carbon-neutral way.

Reference: (Helen, 2011)

Links:
https://www.academia.edu/2865278/Why_Blow_Away_Heat_Harvest_Server_s_Heat_Using_Ther-moelectric_Generators
https://sustainable-procurement.org/fileadmin/templates/sp_platform/lib/sp_platform_resources/tools/push_resource_file.php?uid=6296a08c

8.9.2 2015: Yandex, Mäntsälä, Finland

In 2015, a 4 MW heat pump that utilises the excess heat from the Russian Yandex data centre was installed in Mäntsälä. Heat exchangers extract hot air from the data centre servers at temperatures of around 40°C. Then, the heat pump increases the temperature to about 85°C. The heat pump is optimised to achieve a high COP, potentially exceeding 4.0.

By extracting excess heat from the data centre, 75% of the electricity originally used can be reused. The excess heat replaces natural gas heating, reducing the annual carbon dioxide emissions with approximately 4000 tonnes in the first years and up to 11 000 tonnes in later years. The heat pump can supply 1500 homes with heating through the district heating network. Once the district heating network is expanded, this number will rise to about 4000 homes.

Link:
https://www.reuseheat.eu/wp-content/uploads/2018/03/6.1-Other-experiences-25-case-studies.pdf

8.9.3 2017: Bahnhof, Stockholm, Sweden

Bahnhof has implemented data centre cooling with heat recovery at multiple sites in Stockholm. In the solution used in its data centres, Bahnhof employs Carrier heat pumps to generate cooling for the data centre and uses the district heating network to transfer the excess heat for recovery. Bahnhof's cooling system was designed with excess capacity and is connected to the Stockholm district cooling network. Consequently, the heat pumps' full capacity can be utilised from the start since, in addition to the data centre's excess heat, energy for heat production is also provided by the district cooling network's return pipeline. Thus, in addition to cooling its data centre, Bahnhof provides heat to the district heating network and cold to the district cooling network.

Link:
https://stockholmdataparks.com/wp-content/uploads/customer-references-bahnhof.pdf

8.9.4 2019: Meta, Odense, Denmark

After Facebook's (now Meta) new data centre in Odense was inaugurated in 2019, a collaboration between Fjernvarme Fyn and Facebook was established to utilise the data centre's excess heat. The 165 GWh of free excess heat from the data centre's server halls supported by 100% renewable electricity are distributed to around 7 000 households in Funen, Denmark's third-largest island. A recent system expansion has enabled up to 11 000 households to be heated with recycled, renewable heat from Meta's data centre. Currently, the two large heat pumps on site have a total thermal output of 47 MW.

Links:
https://www.fjernvarmefyn.dk/nyheder/fjernvarme-fyn-i-fokus-ved-indvielsen-af-facebooks-nye-datacenter
https://datacenters.atmeta.com/wp-content/uploads/2023/05/Denmark-Odense.pdf
https://www.ramboll.com/projects/energy/meta-surplus-heat-to-district-heating

8.9.5 2019: Binero, Vallentuna, Sweden

In 2019, Binero Group's ultra-modern data centre in Vallentuna, Sweden, was officially inaugurated. It was built in collaboration with E.ON, which operates the local district heating system. The excess heat from the data centre is recycled and used in district heating to heat homes in Vallentuna. Once the data centre is fully developed, the excess heat from the centre could provide nearly a third of the heat supply fed into the district heating network.

Link:
https://binero.com/press-release/binero-group-och-e-on-inviger-miljosmart-datacenter-i-vallentuna/

8.9.6 2020: GleSYS, Falkenberg, Sweden

In the city of Falkenberg, part of the heat required for the district heating system comes from excess heat from a data centre built by GleSYS in 2020. The excess heat is recovered via a heat pump and sent to the district heating network.

Link:
https://www.falkenberg-energi.se/fjarrvarme/referenser-fjarrvarme/glesys/

8.9.7 2021: BS Energy, Braunschweig, Germany

In the city of Braunschweig, heat recovery from a data centre has been underway since 2021. The heat recovery is carried out in two steps: excess heat from a server rack air-cooling system is recovered using first an air-to-water heat exchanger and then a water-to-water heat pump. The two-step process is used to raise the temperature of the recovered heat from around 25°C to 70°C, which is the temperature required by the local low-temperature district heating network. This case was a demonstrator in the European project of Reuseheat.

Reference: (Persson et al., 2022)

Link:
https://www.reuseheat.eu/brunswick/

8.9.8 2023: Amazon, Dublin, Ireland

In 2023, at Amazon's Tallaght data centre in Dublin, excess heat started to be captured and transfered from the servers into an air-handling unit to be cooled by a coil of cold water. The water, its own temperature now having risen to about 25°C, then passes through a pipe to an energy centre just outside the data centre, where several heat pumps is rising the temperature to 85°C or 70°C in warm weather. The hot water is used to feed the local district heating system. Once fully operational, the system is expected to heat 47 000 m^2 of local public buildings, 3 000 m^2 of commercial buildings, and 135 flats.

Link:
https://reasonstobecheerful.world/data-center-heat-green-energy/

8.9.9 2023: Trollhättan Energi, Trollhättan, Sweden

Trollhättan Energi has commissioned Bravida to install their new data centre with a focus on heat recovery and the minimisation of energy use. Bravida will design, build, and deliver a scalable data centre. The project includes heat recovery, specifically supplying the excess heat to the district heating network in Trollhättan. The project started in 2022 and was expected to be completed in July 2023.

Link:
https://www.energi-miljo.se/bravida-installerar-energieffektivt-i-nytt-datacenter-pa-uppdrag-av-trollhattan-energi/

8.9.10 Planned: Microsoft-Fortum, Espoo, Finland

Microsoft plans to build data centres in the two Finish cities of Espoo and Kirkkonummi, where it could provide 40% of the district heating needed in the area. The Kirkkonummi data centre is expected to be commissioned in 2025. Recycling excess heat from the emission-free electricity used by the data centres will significantly reduce the region's carbon dioxide emissions and help to keep district heating prices competitive. Under the Espoo Clean Heat programme, Fortum's district heat will be coal-free by 2025 and carbon-neutral before 2030. A significant part of the programme's targets can be achieved using the excess heat from Microsoft's large data centres.

Links:
https://www.fortum.com/data-centres-helsinki-region

https://www.fortum.com/data-centres-helsinki-region/construction-fortums-heat-pump-plant-has-started-microsofts-data-centre-site-kirkkonummi
https://www.datacenterdynamics.com/en/news/fortum-begins-construction-at-finnish-heat-pump-plant-will-use-microsoft-data-center-waste-heat/

8.9.11 Proposed: Prime, Sæby, Denmark

Prime's data centre campus features three hyperscale data centres. This was Prime's most sustainable development in 2023 with 100% renewable energy, a carbon-neutral campus, heat recovery for district heating, and biofuel-powered generators. Excess heat will be recycled to provide district heating from the Saeby Heat Plant to the local community. The three data centres will require 124 MW electricity. The year of commissioning has not been communicated.

Links:
https://primedatacenters.com/denmark-data-center/
https://datacentre.solutions/news/64883/prime-enters-denmark-with-124-megawatt-data-centre-campus
https://primedatacenters.com/blog/prime-enters-denmark-with-124-megawatt-data-center-campus-that-delivers-a-net-positive-environmental-impact/

8.10 COMBINED HEATING AND COOLING - WATER-COOLED DATA CENTRES

As mentioned in Section 8.9, the two primary approaches for removing the heat generated in data centres are air and liquid cooling. Like air cooling, liquid cooling can be used to capture the excess heat and use it for heating applications. Liquid cooling systems cool the equipment directly through water-circuits, so the temperatures at which excess heat can be recovered are elevated, typically in the range of 50-60°C or more. This makes it easy to transfer the heat directly to low-temperature district heating systems.

Reference: (Persson et al., 2022)

8.10.1 2020: ASETEK, Aalborg, Denmark

In 2020, Aalborg Forsyning entered into an agreement to buy excess heat from data centre of the information technology company Asetek's for the municipality's large district heating network. Asetek is a supplier of liquid cooling systems for data centres. In this case, liquid-cooled servers are directly connected to the district heating supply pipe. Through this configuration, 70-80% of all the power that goes into the data centre's servers can be reused as district heating without the need for additional heating via heat pumps.

Reference: (Linnebjerg Rasmussen and Voldgaard, 2021)

Links:
https://www.asetek.com/press-releases/asetek-leverer-spildvarme-til-aalborgs-fjernvarmenet/
https://fjernvarmen.danskfjernvarme.dk/p/magasinet-fjernvarmen/2021-08-19/a/nordjysk-datacenter-leverer-varme-direkte-til-fjernvarmenet/3045/440103/22444341

8.10.2 2021: Darmstadt Technical University, Darmstadt, Germany

The Technical University of Darmstadt has implemented a new cooling design in the next generation of its high-performance computing data centre. Since 2021, the new data centre has been equipped with direct hot-water cooling supplying heat at a temperature of 45°C. This low-temperature excess heat is upgraded with a heat pump and is used for heating purposes on the university's campus. The recycled heat is fed into the return pipe of the local district heating network at this university.

References: (Oltmanns et al., 2020) and (Feike et al., 2021)

8.11 COMBINED HEATING AND COOLING - MANUFACTURERING BATTERIES

Manufacturing battery cells for vehicles require significant amounts of electricity. Most of this electricity usage is converted into excess heat with a low temperature that often leaves the manufacturing site in a water flow having a cooling purpose. This excess heat can also be transferred outside the site gates, such as to a district heating system if the battery factory is connected to such a network. Four Swedish cases concerning planned battery plants and their corresponding heat recycling approaches are presented below.

Outside Sweden, extensive plans exist for many large battery manufacturing plants. According to a survey performed by Ny Teknik, a Swedish technology newspaper, the 2023 plans concerned a total annual battery storage capacity of almost 900 GWh in Europe. The largest plans were in Norway (165 GWh/year), Spain (132 GWh/year), Poland (127 GWh/year), and France (124 GWh/year).

References: (Emilsson and Dahllöf, 2019) and (Bielewski et al., 2022).

Link:
https://www.nyteknik.se/elbilar/kartlaggning-har-ar-batterifabrikerna-som-ar-pa-gang-i-europa/4185757

8.11.1 Planned: Volvo/Northvolt, Gothenburg, Sweden

Volvo and Northvolt plan to develop their NOVO battery manufacturing plant in Torslanda, Gothenburg. The site construction began in late 2023. The factory will manufacture lithium-ion batteries for Volvo´s electric cars. Cold water from the large heat pumps at the Rya sewage plant will be used for cooling at the battery plant. The excess heat generated during manufacturing processes will be returned to the sewage plant to provide district heating.

Link:
https://www.dn.se/ekonomi/goteborgs-losning-jattefabriken-ska-kylas-med-avloppsvatten/

8.11.2 Proposed: Northvolt, Skellefteå, Sweden

Northvolt and Skellefteå Kraft will work together to develop a mutually beneficial solution for district heating connected to the large-scale battery factory that Northvolt is building. The planned annual storage capacity is 40 GWh.

The production of battery cells is energy-intensive; Skellefteå Kraft may be able to reuse the excess heat from the factory, which will be unlocking significant environmental and economical benefits. The press release about the Northvolt and Skellefteå Kraft cooperation states: '*Northvolt and Skellefteå Kraft will work together to develop a mutually beneficial solution for district heating connected to the large-scale battery factory that Northvolt is building. The production process of battery cells is energy intensive and Skellefteå Kraft will be able to reuse excess heat from the factory, which will be important both from an environmental and economical point of view.*' According to the Nordic Investment Bank, Northvolt is investigating the possibility of feeding the excess heat from the plant into the local district heating system.

Links:
https://northvolt.com/articles/skellefteaa-kraft-and-northvolt-in-strategic-partnerhsip-to-develop-sustainable-energy-solutions/
https://www.nib.int/loan/northvolt-ett-ab-22746

8.11.3 Proposed: Northvolt, Borlänge, Sweden

Northvolt and Stora Enso have signed a letter of intent for the purchase of the Kvarnsveden Mill and the surrounding industrial area in Borlänge, Sweden. Northvolt will develop the site into a manufacturing plant for active material and battery cells. The gigafactory was initially planned to start part of its operations in late 2024 but has now been postponed by at least two years. Once fully built, the site will have an annual production capacity of more than 100 GWh of cathode material, which will enable cell assembly at multiple Northvolt facilities. The site will also feature cell production. However, it is unclear whether the excess heat from this battery plant will be recycled.

Links:
https://northvolt.com/articles/northvolt-to-transform-closed-paper-mill-in-sweden-into-new-gigafactory/
https://www.dn.se/ekonomi/northvolt-miljardsatsar-i-borlange/

8.11.4 Proposed: Volvo, Mariestad, Sweden

Volvo's extensive site location study has concluded that the municipality of Mariestad, located near Volvo Group's main powertrain plant in Skövde is the best location for a battery manufacturing plant. The planned site will benefit from the region's industrial and logistics infrastructure and Sweden's rich fossil-free electricity supply.

According to the consultation paper for the environmental permit for the plant, annual electricity demand will be 2.3 TWh with a design capacity of 420 MW. The cooling capacity is estimated to be about 230 MW and the excess heat will be initially sent to the Vänern lake. Some heat may be recycled in the future.

Links:
https://www.volvogroup.com/en/news-and-media/news/2022/aug/volvo-group-starts-process-to-establish-plant-for-battery-production.html
https://www.volvogroup.com/se/about-us/Mariestad.html
https://www.nyteknik.se/fordon/sa-stor-blir-volvos-batterifabrik-i-mariestad/4224679

8.12 COMBINED HEATING AND COOLING – FOOD SUPPLY CHAIN

Refrigeration processes in households produce heat, albeit in small quantities. Cooling and freezing processes in food supply chains generate also heat. In modern supermarkets equipped with many refrigerators and freezers, the amount of heat generated is substantial. This surplus heat can be utilised to heat the entire supermarket and meet its hot water requirements, alternatively, it can be fed into a district heating system.

References: (Rolfsman et al., 2014), (Zühlsdorf et al., 2018), (CLEAN, 2019), (Heerup, 2019), and (Dorotić et al., 2022).

8.12.1 2015: Super Brugsen, Sønderborg, Denmark

Since 2015, excess heat from refrigeration in the supermarket SuperBrugsen in the town of Sønderborg has been sent to the local district heating network. After a fire incident, a new refrigeration system was installed in cooperation with Danfoss. The heat recovery from the cooling system can supply the entire store with space heating and hot water. The cooling system is a carbon dioxide refrigeration unit. The gas cooling temperature is higher than to traditional refrigeration systems, and excess heat can be utilised directly in the district heating network. Thus, there is no need for additional heat pumps to raise the temperature. A 1.8 m^3 hot water storage tank with a reference temperature of 65°C has been installed to supplement the refrigeration system. The supermarket's carbon dioxide emissions have been reduced by 34 % compared to the previous gas-based heating system by recycling excess heat from the refrigeration system.

Link:
https://celsiuscity.eu/wp-content/uploads/2019/11/Energy-optimization-in-a-supermarket-in-H%C3%B8ruphav.pdf

8.12.2 2022: Meny, Frederica, Denmark

Danfoss has installed a heat recovery unit at a branch of the supermarket chain Meny in Frederica, Denmark. Since early 2022, the system has been recycling the heat generated by refrigerators to heat the store's 1 900 m^2 area and provide hot tap water year-round. This resulted in annual energy savings by 90% and carbon dioxide footprint of 6.7 tonnes a year.

Link:
https://assets.danfoss.com/documents/latest/197224/AE406240476781en-000101.pdf

8.13 SEWAGE WATERS

Wastewater can be considered a renewable and locally accessible low-temperature heat source. Treated wastewater contains heat that is typically warmer than both the air and seawater. In urban areas, approximately one-third of the delivered heat is dissipated into the sewage system as excess heat. It has been estimated that the amount of wastewater delivered to the sewage system accounts for 85% of the total water demand.

Sewage water exhibits slight fluctuations in flow rate and temperature throughout the year. Due to its high heat capacity and density, sewage water is a suitable heat source for heat pump systems. Heat pumps installed at wastewater treatment plants can efficiently extract heat from the wastewater, providing a relatively consistent heat supply. Compared to industrial or other excess heat, sewage heat is more resilient in the long term. Despite these advantages, wastewater heat remains largely untapped globally.

Heat from sewage water constitutes Sweden's largest proportion of installed heat pump capacity in district heating systems, followed by ambient water and industrial excess heat. Of the 1527 MW total installed capacity in 2013, 47% (more than 700 MW) used sewage water as the heat source.

References: (Averfalk et al., 2017) and (Živković and Ivezić, 2022).

8.13.1 2017: Kalundborg Forsyning, Kalundborg, Denmark

In 2017, a 10 MW electric heat pump that use heat from wastewater to generate heat for district heating, began operating in Kalundborg. At the time, it was the largest heat pump installation in Denmark. The heat pump unit consists of three 3.3 MW heat pumps, and the heat output is controlled by switching the units on and off. The heat pump uses heat from a nearby sewage treatment plant, which has an above-average wastewater temperature due to local industry. Wastewater with a temperature between 20°C and 25°C is sent to the heat pump and cooled to approximately 10°C for heat recovery. The return water from the district heating network is heated from about 55°C to 80°C (potentially up to 86°C).

Link:
https://heatpumpingtechnologies.org/annex47/wp-content/uploads/sites/54/2018/12/annex-47sub-projetcskalundborgwastewater.pdf

8.13.2 2018: Sjölunda, Malmö, Sweden

Using GEA's energy-efficient heat pumps, a sewage plant was considered the best source for heating homes in an innovative approach for turning excess heat into usable heat in Malmö, Sweden. E.ON concluded that GEA's ammonia heat pumps are ideal for district heating in southern Sweden, along with biomass and other renewable energy technologies to mitigate greenhouse gas emissions from heating. With a heating capacity of 10 MW each, four heat pump units were installed near the sewage treatment plant and the waste incinerator in the harbour area of

Malmö, where they were commissioned in January 2018. These heat pumps provide 8% of the total heat supply needed by approximately 100 000 homes.

Reference: (De Jong, 2018)

Links:
https://www.vvsforum.se/2016/05/energijatte-gor-fjarrvarme-av-avloppsvatten/
https://www.gea.com/en/news/trade-press/2021/gea-heat-pumps-at-e.on-malmoe.jsp

8.13.3 2019: Kakolanmäki, Turku, Finland

In 2019, municipalities in the Turku region collaborated to build a new facility to treat the wastewater of the area's 300 000 residents. Wastewater as a heat source is free, stable, predictable, and naturally located close to heat users. In the case of Turku, the Kakolanmäki treatment plant was built underground in the city. The facility includes two 21 MW heat pumps that extract heat from cleaned sewage water and feed 85°C water into the local district heating network. The existing low-temperature network allows the heat to be used without upgrading. The Turku facility produces 302 GWh of heat a year, which is enough to meet the heating needs of 24 000 inhabitants, or 8% of the residents in the area from which the wastewater is collected. The recycled heat has largely replaced burning oil and coal, which is estimated to have reduced the annual emissions by 80 000 tonnes of carbon dioxide. The heat pumps also generate district cooling.

The new treatment plant has also brought other benefits to Turku. The improved water purification has reduced the nutrient load on the local vulnerable sea ecosystem. The recycled fertilisers produced from waste-water sludge reduce the need for virgin fertiliser production, increase the sufficiency of the limited supply of mined phosphorus and avoid emissions of ammonia and the production of nitric acid, two key inputs for nitrogen fertilisers.

Links:
https://www.sitra.fi/en/cases/district-heating-from-waste-water-turku/
https://www.friotherm.com/wp-content/uploads/2017/11/E11-15_Turku-Energia.pdf

8.13.4 2020: Grand Arenas, Nice, France

In the French city of Nice, an excess heat recovery system has been conceived as a low-temperature district heating network sourcing excess heat energy at the outflow batch of a wastewater treatment plant (summer: 25-30°C; winter: 8-13°C). The water is then distributed to the buildings' substations which are equipped with reversible heat pumps to provide the needed heating, cooling, and sanitary hot water to the end users (19 MW of heat and 15 MW of cold). The heat recovery system became operational in 2020.

Link:
https://www.reuseheat.eu/wp-content/uploads/2018/10/D3.1-Best-practices.pdf

8.13.5 2020: Ejby Mølle, Odense, Denmark

Fjernvarme Fyn's newest heat pump plant utilises heat from the wastewater treated at the Ejby Mølle treatment plant in Odense, Denmark. The excess heat temperature is 7-21°C while the district heating supply temperature is 60-69°C. The large electrically driven heat pumps, with a total output of 19 MW, can generate 59 GWh of heat annually, covering the heat consumption of approximately 5 000 households. This corresponds to 5% of Fjernvarme Fyn's annual heat supply. The project also benefits the river's animals and microorganisms. This is because the treated wastewater dissipates part of its heat in the district heating system before it is returned to nature.

Link:
https://www.fjernvarmefyn.dk/nyheder/danmarks-stoerste-varmepumpeanlaeg-baseret-paa-renset-spildevand-leverer-nu-groen-fjernvarme-i-odense

8.13.6 2022: National Western Center, Denver, USA

National Western Center in Denver harnesses heat from a nearby sewer as part its strategy for becoming a net-zero energy campus. The sewer heat recovery system is at the heart of the energy solution. With 3.8 MW, it is also North America's largest sewer excess heat recovery system. The Delgany sewer has the potential to meet over 90% of the heating load of the centre. The project included a radical proposal to re-route part of the untreated sewage stream to collect and transfer heat into an ambient, campus-wide piping distribution loop. The centralised district energy network went live in April 2022 and is reducing the campus's energy use.

Links:
https://www.usengineering.com/2023/02/national-western-center-features-largest-sewer-heat-recovery-system-in-north-america/
https://nationalwesterncenter.com/about/what-is-the-nwc/sustainability-regen/energy/
https://www.districtenergy.org/events/event-description?CalendarEventKey=94cc0201-7deb-4aa7-a162-018ad3261095&Home=%2Fevents%2Fevent-description

8.13.7 2023: De Stichtse Rijnlanden, Utrecht, the Netherlands

In 2022, the construction of the largest heat pump in the Netherlands was given the official go-ahead. The pump is part of an aqua thermal installation that will produce sustainable heat for the Utrecht and Nieuwegein municipalities. The heat pump will be located on the site of the Utrecht sewage treatment plant of De Stichtse Rijnlanden Water Board. If the construction progresses well, the installation will provide 27 MW of sustainable heat by the end of 2023.

The sewage water entering the treatment plant is relatively warm, and about 65 000 cubic metres of wastewater are treated daily. With this installation, heat will no longer be wasted as the heat from the warm purified water will be fed into the heat network. A heat exchanger and the heat pump will raise the temperature of the water to 75°C. This water will then be supplied to the heat network.

When completed, the installation will annually supply 162 GWh of heat to the district heating network. This will be sufficient to provide approximately 20 000 homes with sustainable heat, corresponding to about 15% of the total heat demand of the district heating network of Utrecht and Nieuwegein.

Link:
https://news.eneco.com/start-of-construction-of-largest-heat-pump-in-the-netherlands/

8.14 SUMMARY CONCERNING RECYCLING HEAT

In this chapter, many different heat recycling options have been identified from new activities. These include refineries for non-fossil transport fuels, hydrogen supply and usage, petrochemical processes, electric transformers, new industrial processes, cooling processes, and sewage water treatment plants. Both high-temperature and low-temperature heat sources appeared; low-temperature sources generally require heat pumps to reach temperatures suitable for district heating systems and customers' heating systems. Many of the presented cases involve large amounts of excess heat that can be used to supply large cities.

The main decarbonisation implication of heat recycling is that carbon dioxide emissions can be reduced substantially by implementing one or more of these 13 heat recycling possibilities reported in this chapter, as evidenced by the 72 cases presented. District heating providers should consider these heat recycling possibilities when looking for local decarbonisation options.

9 Supplying heat: Meeting peak demands

Satisfying peak heat demand is the most challenging aspect of heat supply systems from both economic and environmental points of view. This is because additional capacity is needed just at very cold times rather than year-round. Owing to this part-time need for additional heat, oil and natural gas boilers have traditionally been the primary sources for meeting peak load demand. However, to achieve a carbon-neutral economy, the heat sources used to meet peak demand must also be decarbonised.

This chapter deals with three possibilities pertinent to managing periods of peak heat demand. Although some possibilities can be categorised under linear or recycled heat supply, this chapter is dedicated to meeting peak demand due to its criticality. The first possibility concerns heat generation units fuelled with non-fossil feedstocks. The second possibility describes the option of meeting peak demand by using heat storage. The last possibility presents demand-side management schemes by which peak loads are reduced and a fair allocation of heat supply deficits is achieved. The locations of the identified cases are presented in Figure 21.

References: (WSP, 2022), (Energistyrelsen, 2022)

Link:
https://celsiuscity.eu/strategies-for-decreasing-peak-loads-and-energy-use/

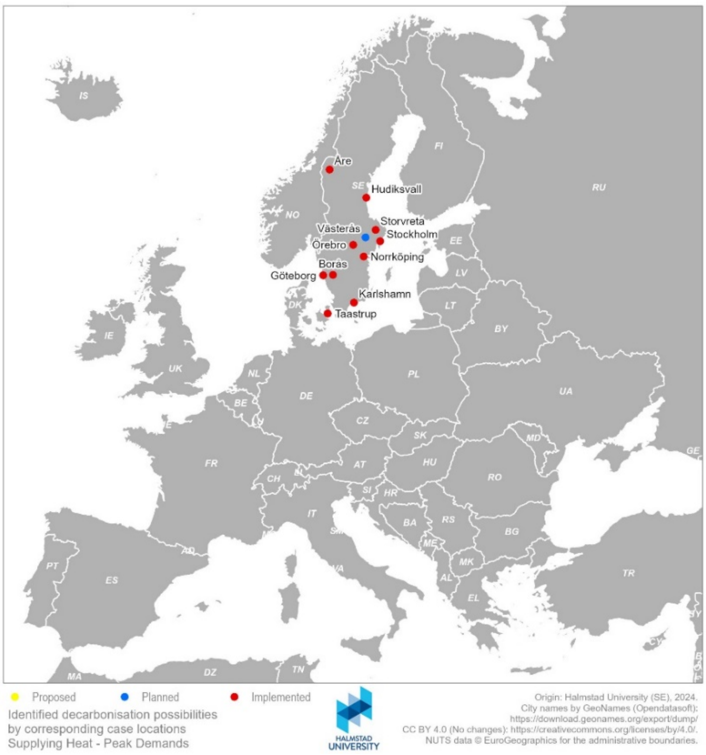

Figure 21. Map showing the locations of cases in the database concerning supplying heat for meeting peak demands.

9.1 PEAK BOILERS WITH NON-FOSSIL FUELS

Peak load boilers are employed when ordinary heat supply facilities experience operational disruptions or particularly cold weather increases the heat demand. Fossil fuel boilers have been, for a long time, the first option to cover peak loads. The two main renewable fuel alternatives are currently wood pellets and bio-oil.

The main disadvantages of pellets are the high investment costs and significant space requirements for the necessary facilities. On the other hand, bio-oil has limited availability as the raw materials used for producing bio-oil with low greenhouse gas emissions are also used for other applications, particularly in the transport sector. Since wood pellets are a solid fuel, their demand in the transport sector is low, which can be a strategic advantage for district heating companies investing in pellets.

Measures to enhance the security of heat delivery at peak times include diversifying technologies and fuels, distributing the production capacity across multiple units, and strategically locating reserve load capacity. These approaches contribute to ensuring a reliable heat supply.

References: (WSP, 2022), (Energistyrelsen, 2022)

9.1.1 2020: Navirum, Norrköping, Sweden

In 2020, Navirum inaugurated a new peak load boiler with 70 MW capacity in the Ingelsta area, Norrköping, Sweden. The new boiler will use bio-oil and work if other district heating plants in Norrköping cannot supply heat. The operating time is estimated to be 300-500 hours per year. The plant is designed to also use wood powder and the use of non-fossil fuels will reduce the annual carbon dioxide emissions with 7 500 tonnes.

Link:
https://bioenergitidningen.se/allt-om-norrkopings-nya-topp-och-reservpanna-for-bioolja/

9.1.2 2022: Göteborg Energi, Gothenburg, Sweden

Göteborg Energi has started to replace its fossil peak boilers with four new units that use refined biomass as fuel. The total capacity of the new units is around 300 MW. The refurbishment of the former Rya peak plant has been completed, and its operation began in 2022. This plant has a capacity of 125 MW. The other three plants, with a total capacity of 140-180 MW, are in the Mölndal, Sävenäs, and Sörred districts of Gothenburg. The commissioning year of these plants running on wood pellets is expected to be 2025, 2026, and 2027, respectively.

Links:
https://www.valmet.com/sv/media/nyheter/press-releases/2020/valmet-bygger-hetvattenpanna-till-goteborg-energi/
https://bioenergitidningen.se/biobransleanlaggningarna-som-goteborg-energi-vill-bygga/

9.1.3 2023: Navirum, Örebro, Sweden

To meet the goal of only selling renewable or recycled heat by 2025, Navirum has switched from fossil oil to bio-oil for one large peak load boiler (130 MW) in Örebro between 2022 and 2023.

Link:
https://bioenergitidningen.se/e-on-i-orebro-fran-fossil-till-fornybar-olja/

9.2 LARGE HEAT STORAGES

Thermal energy storage is a versatile solution that can be utilised for peak shaving through load shifting, as described in Chapter 5. Heat storage enables the heat generated during off-peak periods to be stored and later used during peak hours and days with high heat demand. Thus, heat storage can reduce the utilisation of fossil fuel boilers for meeting peak loads during cold days. This possibility for decarbonised district heating is exemplified by three Swedish cases which use large heat storage.

9.2.1 1983: Vattenfall, Storvreta, Sweden

This heat storage solution, which is described in case 5.6.2, has a remarkable storage size compared to the annual heat delivery from the local district heating system in Storvreta. A heat storage size of 100,000 m^3 and annual heat delivery of 14 GWh result in a relative storage size of 2000 m^3/TJ. This relative storage exceeds all large heat storage solutions identified in the reference below, including the large storage solutions for solar district heating in Denmark. It should be possible to manage all seasonal load variations with the heat storage and running the biomass boiler on constant load throughout the year. Following this approach, the relative storage should exceed 1500 m^3/TJ according to the reference below.

Reference: (Gadd and Werner, 2021)

9.2.2 2018: Adven, Hudiksvall, Sweden

Adven is very pleased with the outcome of the investment in upgrading an old oil storage system to a heat storage system, as described in case 5.6.4 . The cashflow from the investment was higher than expected in the preparation phase. The upgraded system is particularly suitable for meeting peak heat loads during cold days. Both variable costs and carbon dioxide emissions have been substantially reduced.

Other benefits from the heat storage upgrade include the reduced need for continuous crew supervision, easier maintenance breaks, and improved heat supply management year-round, including in the summer when the heat demand can be lower than the minimum capacity of the biomass CHP plant.

Reference: Personal communication with Adven

Links:
https://adven.com/se/fjarrvarme/hudiksvall/
https://energiforsk.se/media/27147/bergrumslagret-i-hudiksvall.pdf

https://www.energi.se/artiklar/har-samlas-fjarrvarme-under-berget/

9.2.3 Planned: Mälarenergi, Västerås, Sweden

This heat storage solution, which is described in case 5.6.7, will have a heat power capacity of up to 90 MW. The hot water reservoir will allow Mälarenergi to heat homes on cold winter days without reducing the electricity generation at the CHP plant, which was done previously. The heat storage system can simultaneously reduce the need to use fossil boilers and increase electricity generation. Therefore, the heat storage investment will have considerable cashflow benefits.

Links:

https://www.nyteknik.se/premium/kraftvarmen-den-dolda-raddaren-i-elsystemet-7037976
https://www.energi-miljo.se/har-byggs-europas-storsta-hetvattenlager/
https://www.bbc.com/news/business-65098792

9.3 ALLOCATION OF HEAT SUPPLY DEFICITS

Typically, a heat network operator lacks direct control over the heat demand in the system since the customers control their heat demand. Traditional optimisation efforts are limited to merely responding to the heat demand as it arises. However, by implementing a smart thermal grid, it becomes feasible to actively manage and control the heat demand instead of just reacting to it. Intelligent district heating offers a financially and technically viable software alternative, or even a potential substitute, for conventional peak supply solutions like peak boilers and large heat storage. This approach facilitates the shift away from the completely consumer-centric perspective in heat demand control by also considering heat supply costs and conditions in heat demand control. Thus, less costly software investments can substitute costly hardware investments in boilers and storage.

Through the implementation of active demand response and demand-side management strategies, a network operator gains the ability to actively control the heat demand while maintaining a high quality of service. These demand-side activities can enable the use of the heat stored in the thermal mass of buildings, as described in Section 5.8.

This level of demand control enables the operator to optimise the operational behaviour of the system, resulting in several benefits. These include the reduction of costly peaks met using fossil fuels, balancing base loads more effectively, aligning demand with market or marginal production prices, and actively lowering return temperatures. The two primary objectives of such control mechanisms are heat load shedding, which involves selectively reducing or shedding loads during peak demand periods, and load moving, which entails shifting the timing of heat usage to optimise system efficiency.

Demand-side management can be implemented through both direct and indirect approaches. An indirect approach involves utilising pricing schemes that incorporate differentiated energy costs based on the current heat load usage. The challenge with indirect approaches is that consumers typically lack the means to act until it is too late, even if they are aware of the pricing dynamics.

On the other hand, smart demand-side management involves the heat supplier having the ability, within certain limits, to directly control heat load usage remotely. This direct approach allows for more precise and immediate control over demand, which can be beneficial for operational management purposes. However, implementing direct approaches can be more challenging as they often require investments in hardware infrastructure and the development of advanced software. A high level of control achieved by demand-side management systems enables the fair allocation of heat supply deficits among customers when demand peaks inevitably occur.

Reference: (Johansson, 2014)

9.3.1 1990: Borås Energi & Miljö, Borås, Sweden

Borås Energi & Miljö introduced in 1990 a billing system for the customers with the highest heat demands in multi-family and service sector buildings. The system was based on the maximum water flow capacity required during the year. The subscribed flow capacity is controlled by a flow limiter. If the customer’s subscribed flow is exceeded, the flow for the space heating heat exchanger is reduced, leaving the flow for hot water preparation unlimited.

This billing system can also be used for the allocation of heat supply deficits, by providing lower supply temperatures in the heat distribution network. This technical solution requires only a minor installation in each substation without any interference with the ordinary heat demand control in the customer substation.

Reference: (Werner, 1992)

9.3.2 2012: NODA and Karlshamn Energi, Karlshamn, Sweden

Karlshamn Energi has connected about 90 buildings to a demand side management using an NODA network in their district heating system. The buildings are treated as remote heat storage that Karlshamn Energi can activate from their control room. This additional flexibility is used to reduce peak loads during cold winter days and to decrease heat usage during maintenance downtime in the nearby industry site, which supply excess heat for the base load. The connected buildings represent about 15-20% of the total annual heat demand of nearly 200 GWh in the district heating system.

Reference: (Johansson, 2015)

Links:
https://noda.se/en/offerings/energy-systems/functions-noda-network/
https://noda.se/en/references/karlshamn-energi/
https://smartcitysweden.com/best-practice/430/the-intelligent-district-heating-system-makes-use-of-ai/

9.3.3 2018: Ngenic and Jämtkraft, Åre, Sweden

The energy company Jämtkraft has digitised its district heating network in Åre, Sweden. By using digital technologies, space heating is temporarily reduced when all ski tourists simultaneously have hot showers.

Links:
https://www.nyteknik.se/nyheter/sa-kan-skidakare-duscha-varmt-och-anda-spara-energi/1871586
https://termoinnovation.se/wp-content/uploads/2023/09/45965-1-slutrapport-pdf.pdf

9.3.4 2021: Stockholm Exergi, Stockholm, Sweden

As mentioned in Sub-section 3.4.2, Stockholm Exergi has installed gateways. These data units are connected to district heating substations and allow the district heating system to achieve higher intelligence, efficiency, and resilience during significant disruptions. The gateways facilitate the remote automated collection of heat usage data from end users, making it easily accessible for analysis. Property owners can use this digital platform to control and optimise their heat usage. By leveraging the data collected through the gateways, Stockholm Exergi can enhance its understanding of heating patterns and implement measures to optimise heat usage and improve overall system performance. They can also allocate heat deficits to adress heavy peak demands.

Links:
https://www.stockholmexergi.se/om-stockholm-exergi/arsredovisning-2020/
https://www.stockholmexergi.se/nyheter/vad-ar-det-stockholm-exergi-installerar-i-fjarrvarmecentralerna/
https://www.energi-miljo.se/installerade-gateways-utan-lov/

9.4 SUMMARY CONCERNING MEETING PEAK HEAT DEMANDS

The implication from this chapter is that two possibilities, large heat storages and demand-side activities, exist to meet peak loads in addition to using traditional fuel-based boilers. Some district heating companies still prefer to use peak load boilers, albeit with non-fossil fuels as described in Section 9.1.

In the past, peak heat demand was almost exclusively met using fossil-fuel boilers, while the three identified possibilities provide complete decarbonisation solutions for peak heat supply. Peak heat demand can now be met using these three different options. Each district heating provider must determine the optimal mix of these options for district heating systems.

10 The value chain possibilities

In this concluding discussion and summary chapter, the silo approach used in the previous eight chapters is left behind by focussing on seven cross-cutting strategy groups for the decarbonisation of district heating systems:

1. Degrees of freedom for available possibilities
2. Temperature levels applied in heat distribution networks
3. Heat pumps as tools in district heating systems
4. Digitalisation as a tool for the identification of deviations
5. Supply responsibilities
6. Institutional frameworks
7. Digital planning models

These seven strategy groups involve different cross-cutting possibilities for the district heating value chain. These possibilities contain the results and aggregated experiences from early adopters of decarbonised district heating systems.

10.1 DEGREES OF FREEDOM

This possibility is about the available options and conditions for decarbonisation and the strategies for choosing among proper possibilities. In this report, degrees of freedom are used as an expression for all valid conditions that influence the choice of decarbonisation possibilities. When it is easy to make a choice, the degree of freedom is high; when the choice is limited, the degree of freedom is low.

Four key aspects of degrees of freedom are discussed as possibility cases: the availability of possibilities, new versus existing buildings, new versus existing synergies, and new versus existing systems.

10.1.1 Availability of possibilities

In a fossil fuel society, fossil fuels are used with standardised technologies that are available globally. In this society, district heating systems typically receive heat from CHP plants and local conditions have a minor influence on the choice of technology. Hence, most district heating systems worldwide are similar, with only minor deviations.

In a decarbonised society, more attention is paid to local conditions since not all possibilities are available everywhere. One example is the availability of geothermal heat sources. Due to its location, Iceland has excellent opportunities for the exploitation of high-temperature geothermal heat, making it also possible to generate large amounts of electricity. The temperatures of large geothermal aquifers in France and Germany are lower, but still suitable for district heating in many locations and regions, such as Paris and Munich. In Finland and Sweden, the dominating crystalline bedrocks with low permeability provide almost no opportunities for deep geothermal projects.

Another example is that the annual solar irradiation is higher in southern Europe than in northern Europe. Hence, local conditions concerning solar irradiation will also influence the choice of available possibilities in a decarbonised society.

One insight concerning availability is that efficient decarbonisation is not only about the substitution of fossil fuels in the heat supply. The district heating technology must also be modified to make the substitution of fossil fuels more profitable. One example is the use of large solar collector fields in district heating systems. Large amounts of solar heat can only be used by storing summer heat in large seasonal storages to meet winter demands. Large thermal storages can also be used for other purposes, such as meeting peak demands (section 9.2) and storing unexpected cheap electric heat on windy days (Section 7.7).

Solar collectors have lower heat losses when lower temperatures are maintained in the solar collector circuit, which encourages the use of lower heat distribution temperatures through a central reduction of the return temperature with a heat pump (Section 4.10). Existing temperature errors in heat distribution networks can also be eliminated (Sections 3.5 and 4.9), providing lower heat distribution temperatures. Hence, decarbonisation is often achieved by a group of possibilities supporting each other. The implementation of possibility groups is presented several times in this report, since some district heating systems appear as cases for multiple possibilities.

10.1.2 New versus existing buildings

New buildings have lower heat requirements than existing buildings, since the construction industry has learned how to construct buildings with low heat demands for space heating and preparation of domestic hot water. Existing buildings can be refurbished to reduce their heat demands.

An open research question for many years has been whether decarbonisation efforts should focus on reducing the heat demands in buildings or on more efficient heat supply, (Hummel et al., 2023). The traditional answer to this question has always been that both activities should be performed simultaneously to reach a the new optimal balance between heat supply and heat demands, (Connolly et al., 2014) and (Hansen et al., 2016). Many research results indicate that the total heat demands in European buildings can be reduced by about one percent per year, giving a total reduction of about one third by 2050. These reductions provide a unique opportunity for existing district heating companies with low-to-moderate market shares to sell the released capacity in the district heating infrastructure to new customers.

10.1.3 New versus existing synergies

District heating is mainly about cooperation with societal activities and processes that have excess heat as an unavoidable by-product of their core activities. Through heat recycling, synergies can be created benefitting for both parties in the cooperation. In existing district heating systems, the main applied synergies are the CHP synergy and the waste incineration synergy. Some emerging synergies have also been identified in this report. All these synergies are presented in Table 3.

Table 3. Overview of synergies creating possibilities for heat supply into district heating systems. The three traditional synergies are in italics, while the remaining synergies are new synergies identified in this report.

Possible synergy	Synergy features
1. Combined heat and power	*Excess heat from thermal power generation is recycled into heat distribution networks.*
2. Waste-to-energy	*Excess heat from a waste incineration plant is recycled into heat distribution networks.*
3. Forestry waste	*Forestry waste from forestry management and industries is combusted as biomass in boilers and supplied into heat distribution networks.*
4. Combined heating and cooling – space cooling	Excess heat from space cooling processes is recycled and fed into heat distribution networks by using heat pumps.
5. Combined heating and cooling – large electricity users	Excess heat from concentrated electricity usages is recycled with or without heat pumps and fed into heat distribution networks. Typical suppliers include the food supply chain, electric transformers, large data centres, and manufacturers of electric batteries.
6. Combined heating and cooling – large heat users	Excess heat from concentrated heat usage is recycled with or without heat pumps and fed into heat distribution networks. Examples include fuel refineries and petrochemical plants in the energy sector and material manufacturers in the industry sector.
7. Flexible electricity	Heat is generated in electric boilers and heat pumps when electricity prices are low (windy days) and fed into heat distribution networks.
8. Hydrogen supply	Excess heat from manufacturing hydrogen is recycled and fed into heat distribution networks, since typical electrolysers have heat losses of one fourth to one third of the electricity input. Hydrogen CHP plants can also generate heat to be recycled through the CHP synergy.
9. Carbon dioxide removal	Carbon dioxide removal can be viewed as a synergy, since removed carbon dioxide can generate additional revenue for the district heating system.
10. Sewage waters	Excess heat in sewage waters remaining from domestic hot water usage is recycled and fed into heat distribution networks by using heat pumps.

Fossil fuels will be substituted in the global energy system, following the actions taken for mitigation of climate change, and much less fuel will be used for electricity generation. Hereby, the CHP synergy will lose its dominant position in district heating systems, although hydrogen can be an emerging fuel for CHP plants. Some countries with large quantities of biomass waste from agricultural and forestry operations may have some biomass CHP plants, but current global biomass resources cannot replace the use of fossil fuels in current CHP plants.

The synergy of heat recycling from waste incineration will continue to some extent since non-recyclable burnable waste cannot be deposited in landfills because of legal landfill bans based on climate change reasons for these waste streams.

Hence, district heating companies must identify and apply other synergies to maintain suitable heat supplies for their heat distribution networks. These synergy changes will challenge the planning departments of district heating companies. An alternative strategy can be to employ no synergy that is partly or completely based on heat recycling. By using a linear heat supply from geothermal, solar, or ambient heat, the dependence on a certain synergy can be reduced.

One major synergy related conclusion is that the CHP synergy is internal to the energy sector since electricity and heat are cogenerated. Hence, the benefits of the synergy are kept within the energy sector. Conversely, many of the new synergies involve cooperation across sectors, allowing for the sharing of synergy benefits with other sectors. Both parties in a cooperation must benefit from the cooperation; otherwise, it is not a cooperation.

10.1.4 New versus existing systems

There is one fundamental difference concerning degrees of freedom in new and existing district heating systems. New systems have more degrees of freedom since they can utilise new network configurations for heat distribution (Chapter 4) and new heat supplies (Chapters 7-9).

Existing heat distribution networks are often victims of technology lock-ins since they were originally constructed to obtain heat from plants generating heat via fuel combustion. To meet future market conditions, operators need to learn how to achieve lower heat distribution temperatures in their networks. One major challenge for existing district heating companies is becoming curious about new district heating technologies while still operating traditional district heating systems.

One challenge in designing new networks is the necessary connections of existing buildings with higher heat and temperature demands that will reduce the degree of freedom somewhat. Only new networks with connections of new buildings will have full degrees of freedom in the design phase.

10.1.5 Summary concerning degrees of freedom

When implementing decarbonised district heating systems, attention must be paid to local conditions since not all decarbonisation possibilities are available everywhere. This is a major difference compared to traditional systems, where a generic and standardised technology could be applied everywhere, such as in the CHP synergy.

Another important conclusion concerning the decarbonisation of district heating systems is that decarbonisation is not only about the direct substitution of the heat supply. Substitution possibilities should be combined with indirect possibilities for more efficient heat usage and heat distribution. These combinations of possibilities for using heat, connecting customers, moving heat, storing heat, and supplying heat make the decarbonisation of district heating highly profitable.

10.2 TEMPERATURE LEVELS

The temperature level is a common denominator in all district heating systems. Combinations of supply and return temperatures in heat distribution networks are used to transfer heat from heat supply plants to customers' heating systems. Lower temperatures have been gradually reduced in the heat flow direction when supplying, moving, and using heat by using simple heat transfers in heat exchangers or shunt valves.

Nowadays, traditional systems are called warm distribution networks, to differentiate them from newer cold distribution networks, which are covered in Sections 4.4 and 4.5. In cold networks, heat pumps are used in customer substations to manage the mismatch between low supply temperatures and higher temperature demands. The growing usage of heat pumps in district heating systems is further discussed in the next section of this chapter.

The temperature possibility focuses on the drivers and actions for obtaining low-temperature district heating (LTDH) with references to the possibilities identified in this report. The five cases below concern the required conditions for existing systems, the economic drivers for obtaining lower heat distribution temperatures, and action plans for existing systems, major transformations, and new systems.

10.2.1 Existing systems

In existing warm district heating systems, the demand temperatures are almost always lower than the distribution temperatures. The temperatures can be equal if direct connections without heat exchangers are employed in customer substations. In these systems, the few customers with high temperature demands always set the temperature level for the whole heat distribution network. Customers with lower temperature demands receive almost no financial benefit from their lower temperature demands since they still receive a high supply temperature.

10.2.2 Economic drivers for lower temperatures

The magnitude of an economic driver for lower distribution temperatures is expressed by the cost reduction gradient (CRG). The CRG provides information about the cost reduction obtained from supply technologies and systems when heat is moved at lower temperatures. The value of this gradient varies between 0.07 and 0.7 euro per MWh delivered and °C lower temperature for heat supply technologies, according to the recent IEA-DHC TS2 report (Averfalk et al., 2021).

For systems, the annual CRG varies between 0.1 and 0.6 euro per MWh and °C, indicating that the driving force for reaching lower temperatures varies from system to system.

More CRG estimates are available in (Averfalk and Werner, 2020). Lower values are achieved by systems that use combustion technologies such as CHP plants, while higher values are achieved by non-combustion technologies. These CRG estimates have been obtained by simulating the following nine benefits with lower temperatures in heat distribution networks:

1. **More geothermal heat extracted** from wells with temperatures between 60°C and 100°C since lower temperatures of the geothermal fluid can be returned to the ground.
2. **Less electricity used** in heat pumps when extracting heat from heat sources with temperatures below the heat distribution temperatures since lower pressures can be applied in the heat pump condensers.
3. **More excess heat extracted** from heat sources with temperatures between 60°C and 100°C, since lower temperatures of the excess heat carrier will be emitted into the environment.
4. **More heat obtained** from solar collectors since their heat losses are lower, thereby providing higher conversion efficiencies.
5. **More heat recovered** from flue gas condensation since the proportion of vaporised water (steam) in the emitted flue gases can be reduced when using biomass with a high water content.
6. **More electricity generated** per unit of heat recycled from steam CHP plants since higher power-to-heat ratios are obtained from lower steam pressures in the turbine condensers.
7. **Higher heat storage capacities** since lower return temperatures can be used in conjunction with high-temperature outputs from high-temperature heat sources.
8. **Lower heat distribution losses** due to the lower average temperature differences between the fluids in heat distribution pipes and the environment.
9. **Ability to use plastic pipes** instead of steel pipes for reduction of the installation costs.

These nine benefits are the fundamental economic drivers for all possibilities associated with using lower temperatures in heat distribution networks.

10.2.3 Action plans for existing systems

The applied temperature levels in existing systems can be considerably reduced by eliminating deviations and malfunctions that cause temperature errors in heat distribution networks, substations, and customers' heating systems. These deviations and malfunctions still exist because the economic drivers have been rather low due to the low CRG of CHP plants and boilers.

Action plans for existing systems contain the following three activities:

- Tracking and elimination of high circulation flows in heat distribution networks, according to the possibility in Section 4.9.

- Tracking and reduction of high return temperatures from substation deviations and malfunctions, according to the possibilities in Sections 3.5 and 3.6.
- Tracking and elimination of high customer demand temperatures, according to the possibilities in Sections 2.7 and 2.8.

These three steps are based on the fact that many heat distribution networks can be operated at lower temperature levels, since most radiator systems can be operated at lower temperatures (Section 2.7) once malfunctions are eliminated.

A common objection to this approach is that major investments are required to use lower temperatures including for installation of larger radiators in existing buildings. However, this objection is not valid. Most radiators in existing buildings were originally oversized and current heat demands are much lower than the original design demands. Hence, lower temperatures can be used in existing radiator systems.

The conclusion above is also valid for energy efficiency measures in existing buildings. These measures will reduce the temperature levels in existing radiator systems and provide capacity space for connecting new customers in existing district heating systems. Hence, adopting energy efficiency measures will create new values in current district heating systems.

10.2.4 Action plans for major transformations

In some of the cases referenced in this report, major transformations of existing warm heat distribution networks have been executed. The next paragraphs discuss the transformation strategies employed in three cases.

The Arlanda Airport in Sweden (case 5.1.2) introduced in 2009 an aquifer storage system to meet low-temperature heat demands using a cold district heating network. Excess low-temperature heat is collected during the summer. High-temperature demands are met by a separate network that obtains heat from the northern parts of the Stockholm district heating system. Before the upgrade, the network also delivered high-temperature heat for low-temperature demands, such as ground heating for aeroplane runaways.

The ETH Hönggerberg campus system in Zürich, Switzerland (case 8.8.1) is substituting the existing warm distribution network with a cold distribution network. Different groups of buildings are being refurbished and connected to the new cold network between 2013 and 2026. Heat pumps are used in each group of buildings to meet high temperature demands. The non-refurbished buildings obtain heat from the existing warm network while the transformation continues. Once the transformation is completed, the warm network will be closed.

Stanford University in California, USA (cases 4.6.4 and 8.7.4) finalised in 2015 a major transformation from its old steam distribution network to a new water-based warm distribution network. The introduction of the combined heating and cooling synergy was profitable, since less electricity was used by the new central heat pumps to lift the temperature from the district cooling system to the new district heating system. After the transformation, the old steam system was closed.

The common denominator of these three transformations is that they split heat distribution into a new bottom cycle for low-temperature demands and a topping cycle for high-temperature demands. After the transformation, the topping cycle was either closed (ETH and Stanford campuses) or partly kept for the future (Arlanda Airport). The heat supply in these cycles is or will be supported by heat storages suitable for each temperature level. The separation of the temperature levels brings low-temperature heat to low-temperature demands and high-temperature heat to high-temperature demands. All three transformations adopted a multi-level approach, which is the inner core of the multi-level network configuration reported in Section 4.3.

These transformations provide important insights into how to organise future heat supply units into high- and low-temperature plants serving high- and low-temperature distribution areas. High-temperature supply plants include electric boilers, combustion units, and heat recycling from high-temperature processes. Low-temperature supply plants include heat pumps, solar collectors, and low-temperature heat resources. High- and low-temperature heat storages can then be linked to these two categories of heat supply.

These three major transformations also have similarities with implemented or planned transformations from steam-based to water-based district heating, such as those performed in Copenhagen, Hamburg, Salzburg, and Paris.

10.2.5 Action plans for new systems

An action plan for new district heating systems is summarised by the following six simple recommendations:

- All new buildings should be designed for low radiator temperatures. A forerunner in this respect is the Swiss norm SIA384/1:2009 which prescribes a target value of 40°C for the design supply temperature of new radiators with 50°C as the maximum permissible value.
- Indirect substations should be equipped with heat exchangers with long thermal lengths (at least 6) to manage both low supply and low return temperatures in the networks.
- Choose a network configuration that makes it easy to use lower distribution temperatures, if the heat supply is influenced by high cost reduction gradients.
- Introduce control of the necessary circulation flow in the heat distribution networks.
- Consider using separate temperature levels in areas with both existing and new buildings.
- Use sustainable heat sources available at the location.

10.2.6 Summary concerning temperature levels

The applied temperature level is the most important common denominator for using heat, connecting customers, moving heat, storing heat, and supplying heat.

The most important insight is that it is possible to lower heat distribution temperatures in existing networks without major investments simply by eliminating temperature errors in distribution networks, substations, and customers' heating systems. Lower temperatures will result in lower heat supply costs, partly from the use of more efficient heat pumps with higher COPs or the elimination of heat pumps.

Twenty percent of the identified possibilities in this report concern temperature levels, particularly how to obtain lower levels.

10.3 HEAT PUMPS

Heat pumps can be used in district heating systems to solve situations where the demand temperatures are higher than supply temperatures or to achieve higher efficiencies in supply, storage or distribution of low-temperature heat.

The increasing interest in heat pumps is a major component of the decarbonisation of the global heat supply for buildings. Recent international publications include (IEA, 2022a) and (Lyons et al., 2022) that was written within the European CETO initiative.

A large heat pump was connected to a district heating system for the first time in Europe in the ETH campus district heating system in Zürich in 1943 (Pallua, 2021). Recent publications concerning large heat pumps in district heating systems include (Averfalk et al., 2017), (David et al., 2017), (IEA-HPT, 2019), and (Euroheat & Power, 2022). A German perspective on large heat pumps is presented in (Agora Energiewende and Fraunhofer IEG, 2023). Typical deviations in large heat pumps are reported by (Aguilera et al., 2022), while some future possibilities with large heat pumps are presented by (Lund and Persson, 2016) and (Persson et al., 2020b).

The two possibility cases below concern the role heat pumps in the identified decarbonisation possibilities and the flexibility of heat pumps.

10.3.1 Heat pumps in the identified possibilities

Heat pumps appear in many of the identified decarbonisation possibilities indicating that they can fulfil multiple roles in a district heating system. The 17 heat pump applications covered in this report are summarised in Table 4 with section and case references. The common denominator of these heat pump applications is that low supply temperatures can be upgraded to meet higher demand temperatures.

Beyond the scope of this report, heat pumps can also appear in combustion plants to reduce flue gas temperatures and the moisture content by flue-gas condensers when wet fuels are used.

Table 4. Examples of the 17 possibilities using heat pumps.

Value chain part and when heat pumps are used in conjunction with identified decarbonisation possibilities	**Examples of possibility cases identified in this report**
Using heat: 2.5 Steam delivery from district heating networks	2.5.1 Olvondo 2.5.2 SPHeat
2.6 Temperature boosting to obtain higher demand temperatures	General method in cold networks and suitable method for customers in warm networks with exceptionally high temperature demands.
Connecting customers: 3.2 Local reduction of the return temperature to achieve more efficient heat distribution	3.2.1 Chifeng
Moving heat: 4.10 Central reduction of the return temperature to achieve more efficient heat storage and solar heat supply, according to Chapter 5 and Section 7.6	4.10.1 Marstal 4.10.3 Graz
Storing heat: 5 Extracting more heat from solar thermal collectors by reducing the temperature in the storage during the spring.	5.2.5 Brædstrup 5.5.1 Marstal 5.5.3 Gram
Supplying heat from linear supply chains: 7.4-7.5 Extracting more heat from geothermal sources	7.4.3 Gateshead 7.5.2 Wüstenrot
7.6 Extracting more heat from solar thermal collectors	7.6.1 Marstal 7.6.3 Gram 7.6.16 Graz
7.8 Extracting heat from ambient water	7.8.1 Drammen 7.8.2 Esbjerg
7.9 Extracting heat from ambient air	7.9.1 Svendborg 7.9.2 Silkeborg
Supplying heat by heat recycling: 8.5 Heat recycling from electric transformers in electrical power grids	8.5.1 Stockholm 8.5.2 Milan
8.7 Heat recycling from centralised district cooling	8.7.2 Stockholm 8.7.3 Helsinki 8.7.4 Stanford 8.7.5 Berlin
8.8 Heat recycling from decentralised district cooling	8.8.1 ETH Zürich 8.8.2 Paris-Saclay University
8.9 Heat recycling from air-cooled data centres	8.9.3 Odense
8.10 Heat recycling from water-cooled data centres	8.10.1 Aalborg 8.10.2 Darmstadt
8.11 Heat recycling from battery manufacturing	8.11.2 Gothenburg
8.12 Heat recycling from the food supply chains	8.12.1 Sønderborg 8.12.2 Frederica
8.13 Heat recycling from sewage waters	8.13.1 Kalundborg

10.3.2 Flexibility of heat pumps

In warm heat distribution networks, heat pumps can be operated efficiently by applying heat supply hedging strategies. With high electricity prices, the heat pump can be turned off, providing supply space for other heat supply units with lower operating costs. When the electricity prices decreases, the heat pump becomes competitive again and is turned back on. Thus, the heat pump's operating priority within the energy system changes over time. This hedging strategy is possible since several heat supply and storage units with different cost characteristics are available in most district heating systems.

The same hedging approach cannot be used effectively in cold distribution networks with ultra-low distribution temperatures, where decentralised heat pumps are always required to meet the higher temperature demands of customers' heating systems.

10.3.3 Summary concerning heat pumps

Heat pumps appear in many of the identified decarbonisation possibilities, mainly to increase low supply temperatures to meet the expected temperature demands. Thus, heat pumps can be seen as a general tool in district heating systems to meet high temperature demands by starting from low supply temperatures. In warm heat distribution networks, heat pumps provide additional flexibility and can be operated through a hedging strategy to reduce electricity costs. However, this approach is unsuitable for cold networks.

About one fourth of all identified possibilities in this report involve heat pumps.

10.4 DIGITALISATION

Many of the identified possibilities are related to the ongoing digitalisation process in district heating and cooling systems. The main purpose of system digitalisation is to use available data streams to operate district heating systems closer to the edge in terms of operational stability. This is possible since current systems have by tradition been operated with wide safety margins for temperatures, pressures, and flows. In the past, very few measurements were available for the complex reality of heat distribution networks and substations, so wide safety margins were used to ensure stable operations and avoid missed heat deliveries to connected customers.

The digitalisation of district heating systems has attracted significant attention in recent years. Introductions and overviews are available in (Euroheat & Power, 2023b), (Dansk Fjernvarme, 2023), and (Schmidt, 2023).

One major dilemma concerning digitalisation has been that the district heating industry has been immature in the context of data science. Moreover, the IT industry does not really understand district heating features and priorities. For example, simulation models for electricity systems have been directly applied to district heating issues despite missing important features about thermal inertia, behaviours, pressures, temperatures, and flows in heat distribution networks.

This digitalisation possibility is exemplified by four cases. First, the availability of data streams is discussed. Second, the early actions for digitalisation are summarised. Third, some recent actions are presented with references to the possibilities identified in this project. Finally, proposals for future digitalisation actions are provided.

10.4.1 Past versus current data streams

In the past, the lack of reliable data streams limited the opportunity to monitor and analyse the real-world operation of district heating systems. Heat deliveries to customers were manually recorded annually or monthly using analogue heat meters for manual billing purposes. The supply temperatures in the networks were chosen based on simple theoretical calculations. Moreover, only a few differential pressures in the heat distribution networks were measured and communications were limited by cables going from the point of measurement to the central control room. Heat suppliers did not know what occurred in customer buildings beyond the delivery interfaces. Early computers were expensive and slow, and few employees had any computer experience.

The data stream situation today is completely different. It is easy to measure, transfer, and store measurements from smart digitalised heat meters in substations. The applied temperatures and pressures can be measured and transmitted by wireless communication. Customer temperatures are also measured by the heat supplier. Computers are cheaper and much faster, and it is easy to store large amounts of data, enabling the measurement of heat data with high time resolutions. Younger staff members have excellent computer skills. However, there is still a lack of simple, reliable and quick methods and tools tailored to district heating features.

10.4.2 Early actions for digitalisation

Digitalisation of district heating and cooling started for more than four decades ago with simple digital support tools for supplying and moving heat. An early object for digitalisation in the 1980s was to obtain cost-effective heat supply by regularly planning proper merit orders for available heat supply plants with different cost characteristics. These tools were followed by digital routines for retrospective daily economic efficiencies for heat supply by comparing costs for each daily actual heat supply with the most efficient heat supply.

Capacity estimates were obtained by calculating pressure drops in meshed pipe networks using digital simulation programs. However, these early tools were often based on the same heat load pattern for all customers, neglecting the wide diversity in customer behaviours. Digital maps and registers of heat distribution pipes gradually appeared, allowing for the possibility to monitor and document heat distribution conditions.

The digitalisation of heat meter readings has provided the opportunity to transfer measurements directly from the heat meters to the billing department. However, most errors in heat measurements must still be identified and solved manually.

The common denominators of all these early digitalisation actions is that manual routines were automated using computers. However, these routines were seldom upgraded to utilise the new digital abilities available through computers.

10.4.3 Recent actions for digitalisation

Recent actions for digitalisation are listed below by supply chain segment:

Using heat

- Smart phone apps for customers to track their heat deliveries.
- Identifying peculiar and unexpected daily heat load patterns by tracking customer heat load variations (Section 2.1).
- Identifying peculiar and unexpected customer behaviours by tracking deviations in heat usages (Section 2.2).
- Continuous measurements of secondary supply and return temperatures in customers' radiator systems to identify high temperature demands and inefficient heating systems in customer buildings (Section 2.7).

Connecting customers

- Monitoring connected substations (Section 3.4)
- Tools for the quick identification of malfunctions in substations by continuously comparing heat meter information on heat deliveries and circulated water (Section 3.5).
- Continuous estimation of the fouling situation for all heat exchangers in substations (Section 3.6).

Moving heat

- Tracking actual circulation flows by comparing the actual and calculated supply temperatures to identify unintended circulation flows (Section 4.9).
- Continuous measurement and removal of oxygen in pipes (Section 4.11)
- Continuous measurement of corrosion in pipes (Section 4.12)

Supplying heat

- Heat load management by manipulating the local heat demand to decrease peak loads via the fair allocation of heat supply deficiencies (Section 9.3).

10.4.4 Future actions for digitalisation

The following actions can be implemented in the future by using computers and data communication:

Using heat

- Tracking conditions in customers' radiator systems via the continuous estimation of their effective thermal lengths (Section 2.8) to identify malfunctioning radiator systems within one day.

Connecting customers

- Providing customers with useful information about the status of their substations (excellent, good, average, bad, or awful).
- A new operation strategy of always monitoring the opening of control valves in substations, which allows for the possibility to substitute the current use of differential pressure as the condition for flow delivery.
- Finding new malfunctioning substations in one day.

- Continuous measurements of the pressures in over 100 nodes, which can provide dynamic pressure cones for heat distribution networks.
- Continuous pressure calculations for heat distribution networks using flow measurements from flow meters in all substations.
- Continuous comparison of actual and calculated pressures to quickly identify anomalies.
- Continuous measurement of supply and return temperatures in over 100 nodes, which can provide information about areas with reductions in the supply temperature due to heat losses and areas with high return temperatures.
- Continuous flow balance in networks based on the actual circulation flows to identify unintended circulation flows in one day.
- Continuous heat balance in networks based on the actual heat distribution losses.

10.4.5 Summary concerning digitalisation

The digitalisation of district heating systems is an ongoing process that started about four decades ago. The digitalisation of heat supply planning and monitoring was the first step in this process. Nowadays, digitalisation also covers networks and substations. The next step is to utilise the most recent digital technologies to continuously track several thousands of locations to monitor and understand what is really occurring in networks, substations, and customers' heating systems. This will increase the efficiency of district heating systems compared to traditionally operated networks, where operations were based on estimates and guesses (sometimes formulated in national standards) about moving heat.

The digitalisation possibilities in this report constitute sixteen percent of all identified possibilities.

10.5 SUPPLY RESPONSIBILITIES

In traditional warm distribution networks, heat suppliers have been completely responsible for the availability and reliability of heat deliveries. In these systems based on central supply responsibility, neither peak loads nor supply outages should result in reduced heat deliveries to connected customers. This supply-side responsibility relies on redundancies in both heat supply and heat distribution. The additional costs of these necessary redundancies are included in the price of the district heating service. Hence, customers in district heating networks do not need to have the capacity for back-up heat deliveries.

The two cases below consider shared supply responsibilities and heat storage for reliable heat deliveries.

10.5.1 Shared responsibilities

The decentralised feed-in of heat is a fundamental feature of cold networks in the decentralised CHC configuration (Section 4.5) that can also appear in warm distribution networks (Section 4.8). A common denominator of these decentralised feed-ins is that these heat deliveries do not follow the daily and seasonal variations of the heat demands. Thus, additional heat should be supplied to meet the total heat demands from customers.

The additional heat can be supplied by a decentralised supplier or another supplier in the network. In the latter case, the suppliers' shared responsibility must be defined for all decentralised feed-ins. For example, the degree of supply responsibility is a vital consideration in local heat recycling applications in Stockholm, which are labelled as open district heating. Significant remuneration is provided for decentralised heat suppliers with high supply responsibility.

Links:
https://celsiuscity.eu/open-district-heating-in-stockholm-sweden/
https://c2e2.unepccc.org/kms_object/open-district-heating-in-stockholm-sweden/
https://www.stockholmexergi.se/en/heat-recovery/
https://www.stockholmexergi.se/en/heat-recovery/frequently-asked-questions-about-open-district-heating/

10.5.2 Heat storages for reliable heat delivery

Large heat storage can provide a high degree of supply responsibility (according to Section 9.2) since it can quickly provide a large amount heat supply. In the future, owners of heat storage may provide special responsibility contracts to heat users interested in taking a more active role in the district heating system. They may become decentral heat suppliers or prosumers.

District heating operators can also motivate implementations of large heat storage by including a time guarantee (such as two, three, or four weeks) in heat delivery contracts, providing and selling reliable heat deliveries independent of unexpected peak loads or supply outages. Governments and municipalities can also request similar time guarantees in legal documents to ensure safe heat deliveries and increase customer trust in district heating.

10.5.3 Summary concerning supply responsibilities

In traditional district heating systems, peak and back-up boilers meet the supply responsibility for all customers. In the future, large heat storage could inherit this responsibility. These two cases presented above can be summarised by the following question: will large heat storage be able to share the future supply responsibility with demand side management and traditional peak boilers?

10.6 INSTITUTIONAL FRAMEWORKS

The institutional frameworks for district heating and the context for the expansion of these systems vary significantly by country. Countries with high market shares have generally developed legal and market instruments to achieve efficient heat markets with safe and secure heat deliveries and pleased customers. Conversely, these institutional frameworks are usually unavailable in countries with a low market share of district heating. An recent overview of the EU context of institutional frameworks for district heating is provided by (Billerbeck et al., 2023).

The six possibility cases for institutional frameworks concern energy accounting, greenhouse gas emissions accounting, carbon dioxide removal, bans on fossil fuel boilers, support schemes, and district heating research.

10.6.1 Energy accounting

The framework conditions for international and national energy statistics are provided in the United Nations International Recommendations for Energy Statistics, which was adopted in 2011 and finally published in 2017. These recommendations rely heavily on the IEA's experience in supervising global energy markets since the two international oil embargos in the 1970s. The IEA's routines for energy statistics are briefly explained in the 2005 IEA Energy Statistics Manual, while more in-depth explanations are available in the 2023 database documentation of the IEA World Energy Balances. These international energy statistics have four dimensions:

- Geographical units, such as nations and regions
- Years
- Community sectors
- Commodity flows for energy products.

Primary energy supply and final energy consumption are the only two interfaces reported. Activities beyond final energy consumption are not included. Thus, neither heat losses from transportation nor the efficient use of electricity in heat pumps are included in energy statistics.

The IEA's statistical routines assume linear energy supply chains, as applied in the fossil fuel society. Fundamentally, energy demand is linked to a primary energy supply according to the first law of thermodynamics. Consequently, the heat recycling feature of district heating is neither recorded nor included in the IEA energy balances, which lack recycled heat as a commodity flow.

Heat recycling is featured in a secondary sequential heat flow from an original energy conversion process using a primary energy supply to meet a primary purpose. Examples of primary purposes include thermal power generation, industrial processes, and waste incineration. Excess heat from various sectors can be gathered for heating purposes in buildings through district heating systems. However, this transfer of heat between sectors is not recognised in current international routines for energy statistics.

This has the following implications for energy statistics related to district heating systems:

- In CHP plants, the heat recycled to district heating is visible, but the primary energy is allocated proportionally to the electricity and heat outputs. Thus, the recycled heat has the same primary energy supply as the heat provided by traditional boilers. All benefits of cogeneration are allocated to electricity generation and no benefit is allocated to heat recycling.

- In industrial energy supply and processes, the heat recycled to district heating is never reported properly. Thus, the primary energy supply is entirely allocated to the primary purpose. The recycled heat is not associated with any primary energy supply.
- In waste incineration plants, the calorific value of the waste indicates the primary energy supply. Since most plants operate in CHP mode, the same features discussed above apply. The implication for district heating systems is that recycled heat is associated to environmental problems linked to waste incineration. Thus, the responsibilities for these problems are moved from the waste sector to the energy sector. This transfer of responsibility violates the polluter pays principle. The primary purpose of waste incineration is reducing methane emissions from landfills since many countries have already introduced landfill bans on organic and burnable waste.

A possibility for district heating is to revise the inaccurate statistical routines described above. The revision should consider the polluter pays principle and the societal benefits of heat recycling. This can increase the interest of customers and society as a whole in district heating based on heat recycling. The revision should include the following three activities:

- Introduce a commodity flow for heat recycling in international energy statistics.
- Allocate all primary energy flows to the primary purpose in the sequential supply chain.
- Define heat recycling as the secondary purpose with no primary energy supply.

The three activities suggested above align very well with the basic principles for waste concerning environmental product declarations (EPD) advocated by EPD International.

References: (IEA, 2005), (United Nations, 2017), (EPD International, 2021), and (IEA, 2023)

10.6.2 Greenhouse gas emissions accounting

National greenhouse gas emissions must be reported to the UNFCCC every year by following the IPCC's guidelines for greenhouse gas inventories. These guidelines consider emissions in five different baskets: energy supply, industrial processes, agriculture, land use together with land-use changes and forestry (LULUCF), and waste, according to (IPCC, 2006a).

For district heating systems, greenhouse gas emissions are recorded in the following baskets according to the energy and heat inputs:

- Fossil fuels: all carbon dioxide emissions are gathered in the energy basket, according to the IPCC guidelines for energy supply (IPCC, 2006b).
- Heat recycling from industrial processes: no carbon dioxide emissions are allocated to district heating since no commodity flow for heat recycling exists in energy accounting. Industrial companies are responsible for the primary energy supply and the corresponding greenhouse gas emissions.

- Biomass: all biogenic carbon dioxide emissions are recorded in the LULUCF basket since these emissions belongs to the forestry sector. The argument for using this basket is that biomass usage belongs to the natural coal cycle and not to the additional fossil carbon cycle. Thus, the emission factor for biomass in the energy supply is zero and the national forestry sector is responsible for the carbon dioxide emissions from bioenergy used in the energy sector.
- Waste: all fossil-based carbon dioxide emissions are recorded in the energy basket when waste incineration is used for energy purposes since waste is primary energy supply according to the energy accounting principles of the UN and IEA. When waste incineration is performed without energy recovery, all emissions are recorded in the waste basket. The biogenic carbon dioxide emissions belong to the LULUCF basket.

The emissions from district heating systems are recorded following the same statistical routines for primary energy supply in international energy accounting described in the previous sub-section. Thus, the same deficiencies concerning district heating that occur in energy accounting apply to for greenhouse gas emissions accounting. The reason for this strong connection between energy and emissions accounting is that the IPCC National Greenhouse Gas Inventories Programme was managed by IPCC’s Working Group I in close collaboration with OECD and IEA from 1991 until its transfer in 1999 to the IPCC's Task Force on National Greenhouse Gas Inventories based in Japan.

Since emissions from biomass combustion are recorded differently than emissions from other fuels in district heating systems, attention must be paid the upper limit for biomass use. Otherwise, the forestry sector can move too much forestry carbon into the atmosphere, causing additional climate change in the same manner as fossil carbon dioxide emissions.

As stated above, nations report carbon dioxide emissions from biomass under memo items in their national inventory reports to the UNFCCC. These emissions should not be included in the national total emissions from the energy sector. The amounts of biomass used as fuel are included in the national primary energy supplies. However, the corresponding carbon dioxide emissions are not included in the national total as it is assumed that the biomass is produced sustainably . If the biomass is harvested at an unsustainable rate, net carbon dioxide emissions are accounted for as a loss of biomass stock in the LULUCF basket.

No general international rule or commitment defines a sustainable rate of biomass harvestings. A common view is that the annual harvest should not exceed the annual forestry growth. However, the European Union says that European forestry resources should be kept as a long-term sink to compensate for unavoidable future carbon dioxide emissions.

This view and the corresponding political decisions are expressed in (European Union, 2023) issued on 19 April 2023, which states that the total EU LULUCF greenhouse gas sink should be 310 million tonnes in 2030. This total ceiling for all member countries is also allocated to each member state by national ceilings in 2030. Hence, this emission ceiling is similar to the EU’s ceiling for fossil carbon dioxide emissions.

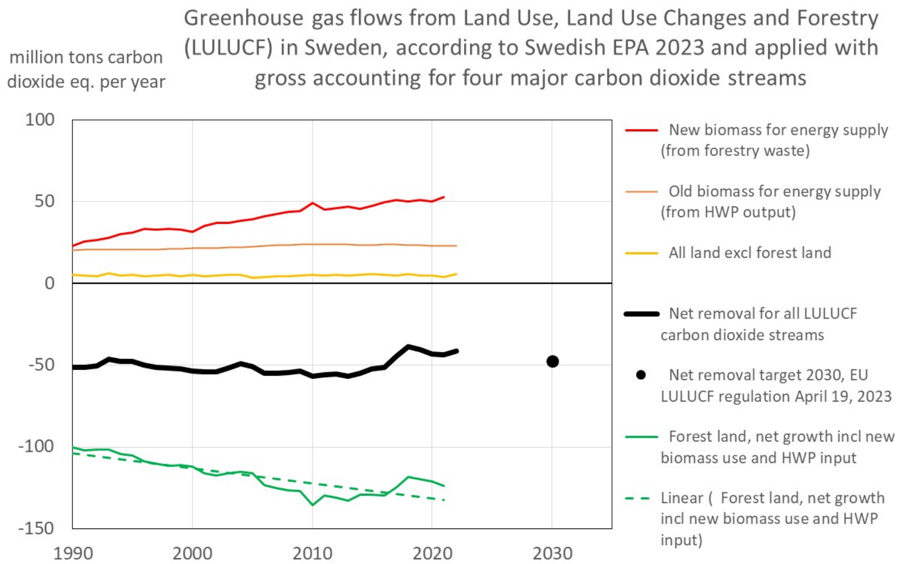

Figure 22. Greenhouse gas emissions from Land Use, Land Use Changes and Forestry in Sweden in 1990-2021, and partly of 2022.

As an example, an overview of Sweden's emissions from LULUCF is illustrated in Figure 22. The figure shows the four major flows of greenhouse gas sources and sinks and the net removal (the thick black line). The 2022 net removal was 41 million tons, while the allocated 2030 EU target is 47 million tons. Therefore, the Swedish forestry sector must eliminate 6 million tons of biogenic carbon dioxide by 2030. These excess emissions hinder the EU's commitment to using forestry as a sink for future unavoidable greenhouse gas emissions.

The above discussion about greenhouse gas emissions accounting for district heating systems has highlighted two major considerations:

1. The international carbon dioxide accounting system is less transparent for district heating systems since heat recycling is not acknowledged as a commodity flow in energy statistics and carbon dioxide emissions are presented in different baskets with different basic principles.
2. The European Union has introduced an upper limit for biomass usage in the LULUCF sector through new regulation in April 2023.

The district heating sector could call for a harmonisation of the greenhouse gas emissions accounting principles with the proposed revision of the energy accounting principles for district heating suggested in the previous sub-section. This can increase societal and customer interest in district heating. It will also put pressure on the owners of the primary purposes to decarbonise their primary processes.

10.6.3 Carbon dioxide removals

District heating systems that use heat from biomass and waste combustion have indirectly created hubs for biogenic carbon dioxide removals since biomass and waste are transported by vehicles to central combustion plants. This high concentration of biogenic carbon dioxide emissions is an added value for district heating providers since large volumes of biogenic carbon dioxide can be removed efficiently when working with such high concentrations. This promising synergy is covered in Sub-section 10.1.3.

According to Chapter 6, no international remuneration scheme exists for carbon dioxide removal. This deficit could be addressed by including biogenic carbon dioxide removals in the European Trading System as a special LULUCF basket.

National remuneration schemes for carbon dioxide removal have recently appeared in Norway and Denmark. A similar remuneration scheme has been planned for Sweden and is awaiting the final decision from the Swedish parliament.

10.6.4 Bans for new and existing fossil fuel boilers

International bans on fossil boilers have not yet appeared. In the EU, this issue was addressed in the negotiated compromise text from 7 December 2023 for the recast of the Buildings Performance Directive. Related to Article 3, policies and measures should promote 'the phase out of fossil fuels in heating and cooling with a view to a complete phase-out of fossil fuel boilers by 2040'. Article 7 should contain 'requirements for Member States to ensure that from 2028 new buildings owned by public bodies, and then from 2030 all new buildings, are zero-emission buildings.'

Some national bans have been implemented by pioneering EU member states. An overview of the 2022 situation is presented by (Braungardt et al., 2023). The 2023 situation is reported in the below links to the European Heat Pump Association (EHPA). The current and announced bans on fossil heating equipment in Europe can be summarised as follows:

- Oil and gas in all buildings: Norway, Denmark, Ireland, The Netherlands, and Germany.
- Oil and gas in new buildings: United Kingdom, Luxemburg, and Italy.
- Oil in all buildings and gas in new buildings: Belgium, France, and Austria.
- Oil in new buildings: Slovakia.

Links:
https://data.consilium.europa.eu/doc/document/ST-16655-2023-INIT/en/pdf
https://www.ehpa.org/news-and-resources/news/fossil-fuel-heating-too-few-eu-countries-have-committed-to-phase-out/
https://www.ehpa.org/news-and-resources/position-papers/industry-ngo-joint-statement-in-support-of-a-phase-out-of-fossil-fuel-boilers-and-a-switch-to-clean-heating/
https://www.ehpa.org/news-and-resources/news/german-heating-law-watered-down-but-end-goal-unchanged/
https://www.ehpa.org/news-and-resources/news/which-countries-are-ending-fossil-fuel-heaters/

10.6.5 Support schemes for decarbonised district heating

Both regulatory and financial support schemes exist at the EU and national levels. Recent updates aim to increase the competitiveness of decarbonised district heating.

One important EU regulatory framework is the new recast of the EU Energy Efficiency Directive from October 10, 2023. Article 26 of this directive contains four energy conversion activities about considering heat recycling when new or refurbished plants are planned and implemented. The four activities are thermal power plants above 10 MW input, industrial installations above 8 MW input, service facilities above 7 MW input, and data centres above 1 MW input. Following this directive, these activities can no longer be ignored in the planning phase, unless a cost-benefit analysis proves that heat recycling is not profitable.

Another important EU regulatory framework is the Emission Trading System (ETS), which was started in 2005. By 2027, it will be extended by an additional trading system, called ETS 2, which will include buildings and transport. It will be an upstream solution for fuel deliverers to those two sectors. As the prices of emission rights increase, it will be more expensive to heat buildings with fossil fuels. The ETS 2 will be combined with a Social Climate Fund and a price ceiling for emissions rights until 2030.

An important EU financial support scheme is the Innovation Fund, a developing programme for the demonstration of innovative low-carbon technologies. The fund focuses on highly innovative clean technologies and big flagship projects with European added value that can bring significant emission and greenhouse gas reductions. It is financed by revenue from the ETS. The planned grant budget for 2020-2030 is 40 billion euro. By January 2024, project grants of 6.5 billion euro had been signed for 106 projects from the 2020, 2021, and 2022 calls. The planned deadline for the 2023 call was April 2024. The four decarbonisation cases reported in Table 5 have received funding from the Innovation Fund.

Table 5. Cases in this report that have received funding from the EU Innovation Fund.

Project name	Case in this report	Country	Innovation Fund grant, million euro	Planned implementation year
BECCS Stockholm	6.1.1	Sweden	180	2026
EAVORLOOP	7.2.12	Germany	91.6	2026
Holland Hydrogen	8.2.3	Netherlands	89	2027
HYBRIT	8.6.5	Sweden	143	2027
Total			504	

Examples of national activities concerning funding and supporting activities for decarbonised district heating are provided below from Germany, Czechia, France, the Netherlands, and the USA.

In Germany, the government announced in June 2023 its ambition to triple the district heating connections by 2045. The goal is to reach 18 million inhabitants with district heating from the six million already connected today. Furthermore, a

2.98 billion euro programme (Bundesförderung für effiziente Wärmenetze) was recently implemented in Germany to support decarbonisation in existing and new district heating systems. The Support DHC project will be actively linked to this German decarbonisation programme. This research project is co-funded by the LIFE Programme of the European Union and one supporting partner is Halmstad University.

In Czechia, a 1.2 billion euro programme is promoting the decarbonisation and modernisation of heat generation units. The programme will run until January 2026 and is financed by the EU's Modernisation Fund.

In France, decarbonisation projects involving geothermal, solar, biomass, and heat pump actions in district heating systems can obtain grants through ADEME's 'Fonds Chaleur' programme since 2009. The fund had an annual budget of 370 million euro until 2021, it was increased to 520 million euro from 2022, and will reach the level of 820 million euro from 2024. On 22 December 2023, the French Ministry of Energy Transition published the finalised action plan for accelerating the development of the geothermal energy sector. The plan supports the use of geothermal energy to sustainably meet the heating and cooling needs of individual and collective buildings in France.

In the Netherlands, the Groningen gas field was closed down on 1 October 2023 to reduce earthquake risks after an earthquake in 2012 damaged several buildings. This closure marked the end of 60 years of supplying natural gas to Dutch homes. As a result, other heat supply methods, such as district heating, are now needed in the Netherlands.

In the USA, decarbonised district heating systems can benefit from the Inflation Reduction Act, according to an article in the Q1 2023 issue of District Energy (see the last link provided below).

Links:
https://energy.ec.europa.eu/news/new-energy-efficiency-directive-published-2023-09-20_en
https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/ets-2-buildings-road-transport-and-additional-sectors_en
https://cinea.ec.europa.eu/programmes/innovation-fund_en
https://climate.ec.europa.eu/system/files/2022-07/if_pf_2022_beccs_en.pdf
https://climate.ec.europa.eu/system/files/2023-04/if_pf_2023_eavorloop_en.pdf
https://climate.ec.europa.eu/system/files/2022-12/if_pf_2022_hh_en.pdf
https://climate.ec.europa.eu/system/files/2022-07/if_pf_2022_hybrit_en.pdf
https://ec.europa.eu/commission/presscorner/detail/en/IP_22_4823
https://www.euractiv.com/section/energy-environment/news/germany-aims-to-connect-100000-buildings-to-district-heating-every-year/
https://www.bafa.de/DE/Energie/Energieeffizienz/Waermenetze/Effiziente_Waermenetze/effiziente_waermenetze_node.html
https://www.euroheat.org/dhc/eu-projects/supportdhc
https://ec.europa.eu/commission/presscorner/detail/es/ip_22_7680

https://presse.ademe.fr/2023/05/fonds-chaleur-2022-520-millions-deuros-engages-au-profit-de-plus-de-900-nouvelles-installations-de-chaleur-renouvelable-et-de-recuperation.html
https://prod.euroheat.org/news/latest-news-on-the-european-distict-heating-and-cooling-market
https://www.thinkgeoenergy.com/france-finalizes-action-plan-for-geothermal-sector-development/
https://www.europeangashub.com/groningen-gas-field-the-end-of-an-era-but-the-timing-is-unfortunate.html
https://www.districtenergy-digital.org/districtenergy/library/item/q1_2023/4073104/

10.6.6 District heating research

The decarbonisation of the European district heating sector has been supported by several significant EU research projects. The resources available for these projects were initially very low and increased substantially after 2013, as shown in Figure 23. The peak, about 100 million euro per year, was reached between 2018 and 2020. Resources available for research was then reduced since, from 2021 onwards, implementation actions have been prioritised. As a result, the Horizon Europe programme has provided fewer research resources than the previous Horizon 2020 programme.

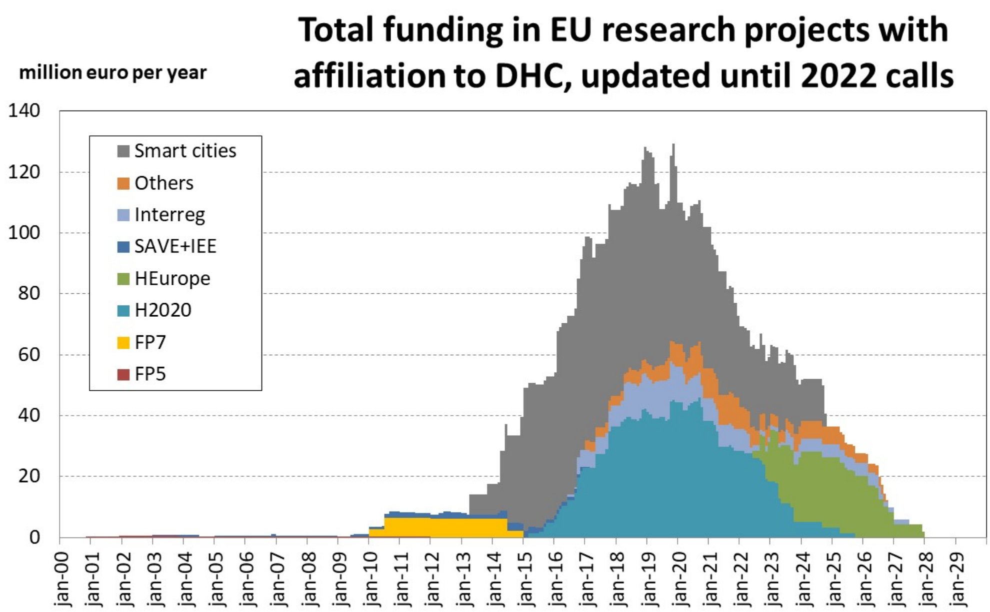

Figure 23. Financial resources available for DHC research projects supported by EU programmes. Support from the EU Innovation Fund is not included. The average budget of the represented 134 projects is 7.1 million euro.

The total research grants in Figure 23 is almost one billion euro and has provided vital input for universities and other organisations to develop and improve district heating technology, methods, and competitiveness. These research activities are expected to influence the European district sector in the 2030s through both new ideas and contributions from young professionals participating in these projects.

10.6.7 Summary concerning institutional frameworks

The six cases associated with institutional frameworks can all be refined to provide more support for the decarbonisation of district heating systems. Both the energy and greenhouse gas emissions accounting systems can be revised to better align them with the characteristics of district heating, particularly the heat recycling feature. Biomass-based systems can be used to remove biogenic carbon dioxide from the natural coal cycle if appropriate remuneration schemes are introduced to reduce emissions. The expected bans on fossil fuel boilers will create a market for fossil-free heat from district heating and individual heat pumps. Financial support will still be required for promising technologies and methods relevant to district heating systems to reduce adoption risks. District heating research will need to continue to obtain more efficient and competitive district heating systems.

10.7 DIGITAL PLANNING MODELS

In recent years, comprehensive digital planning models have been developed in some European research projects as a new digitalisation activity. The purpose has been to aggregate local conditions at the regional and national levels to better frame potential extensions of existing systems and new systems.

Progress has been made by using available data in these digital models for both research and local implementation purposes. Geographical Information Systems (GIS) are central tools in these planning models. The open datasets used in this possibility include population densities, current district heating systems, current waste-to-energy plants, current locations of industrial excess heat, and current geothermal resources.

Three cases concerning the possibility of digital planning models are presented below : the Heat Roadmap Europe (HRE) project cluster and two national analyses for Italy and Sweden.

10.7.1 2012: Heat Roadmap Europe

The first pre-study in the HRE cluster (Connolly et al., 2012), which was summarised in (Froning, 2012), focused on the current situation of district heating in the EU. The annual economic benefit from district heating supplying 50% of European buildings was estimated to be 14 billion euro. The second pre-study (Connolly et al., 2013), which was summarised in (Editorial, 2013), had a long-term focus with the same market share. This annual economic benefit in 2050 was estimated to be 100 billion euro.

The main novelty of early HRE pre-studies was the combination of temporal energy system modelling and spatial energy landscape mapping. This combination allowed for the inclusion of unique local conditions in forecasting and planning, which facilitated the recognition and implementation of district heating opportunities. The two pre-studies mentioned above served as a test-bed for new ideas. The IEE project of Stratego, 2014-2016, also known as HRE3 (Connolly et al., 2015), was the first real application of the new possibility. Through this project, the Czech Republic, Croatia, Italy, Romania, and the United Kingdom were examined with the new combined methodology, where a soft link was used between the national level energy system modelling and square kilometre-scaled spatial mapping.

The Heat Roadmap Europe 4 project (2016 – 2019) aimed to develop national low-carbon heating and cooling strategies called heat roadmaps to quantify and implement national changes for 14 EU member states, which accounted for 85-90% of EU's total heating and cooling demand. The 14 member states were Austria, Belgium, the Czech Republic, Finland, France, Germany, Hungary, Italy, the Netherlands, Poland, Romania, Spain, Sweden, and the United Kingdom. As a continuation of the HRE cluster project, the sEEnergies project (2019 – 2022) aimed to conduct a comprehensive assessment and quantification of the policy impact of the energy efficiency first principle. Moreover, the project developed a holistic framework that considered the synergies between sectors to maximise energy savings.

In the fifth part of Heat Roadmap Europe in 2023, the potential to expand the market share of district heating in the EU was estimated to be 20% by 2030 and 48% by 2050. Strategic planning is necessary to develop 18 500 new district heating systems, which will require infrastructure investments of about 680 billion euro by 2050.

Several international scientific papers have been published from the HRE project cluster. The optimal offset between heat supply and demand was explored by (Connolly et al., 2014, Hansen et al., 2016). Strategic heat synergy regions were identified by (Persson et al., 2014). The electricity, heating, and cooling sectors were compared by (Connolly, 2017). Real implementations of large heat pumps in district heating systems were identified by (David et al., 2017). All steps behind the development of the Pan-European Thermal Atlas (PETA) were presented by (Möller et al., 2018). The latest version of the PETA is available by the last weblink provided below. The whole European Union was sliced into 440 million hectares and the expected heat distribution cost per hectare was estimated by (Persson et al., 2019), while EU-wide local heat supply strategies were presented by (Möller et al., 2019). Finally, the strategic heating transition typology as a basis for policy recommendations was addressed by (Paardekooper et al., 2022).

The elaborated HRE methodology has also been applied to other areas, such as in the Heat Roadmap China and the Heat Roadmap Chile.

Links:
https://vbn.aau.dk/files/77244240/Heat_Roadmap_Europe_Pre_Study_1.pdf
https://vbn.aau.dk/files/77342092/Heat_Roadmap_Europe_Pre_Study_II_May_2013.pdf
https://vbn.aau.dk/da/publications/heat-roadmap-europe-3-stratego-translating-the-heat-roadmap-europ
https://www.euroheat.org/dhc/eu-projects/stratego
https://heatroadmap.eu/project/
https://cordis.europa.eu/project/id/695989
https://api.euroheat.org/uploads/Heat_matters_the_missing_link_in_RE_Power_EU_Aalborg_University_2023_f362bc76ba.pdf

https://www.seenergies.eu/
https://euf.maps.arcgis.com/apps/webappviewer/index.html?id=8d51f3708ea54fb9b732ba0c94409133

10.7.2 2021: Italy

The district heating possibilities in Italy were explored in a national project that aimed to show the unexploited potential of waste and renewable heat in Italy through the detailed mapping of these sources using the HRE methodology. The aim was to highlight areas with high heat recovery potential that could be exploited through the expansion of district heating systems. The recoverable heat sources were analysed in terms of their location and recovery aspects with a focus on temperature levels and technological implications for temperature upgrades.

Reference: (Dénarié et al., 2021)

10.7.3 2022: Sweden

The solar district heating possibilities in Sweden are currently being explored using the HRE methodology in a project financed by the Swedish Energy Agency. Case studies are being conducted for three locations with large solar collector fields, pit heat storage, and large heat pumps to be used during windy days with low electricity prices.

Link:
https://termoinnovation.se/projekt/soldriven-fjarrvarme-med-groplager-for-svenska-forhallanden/

10.7.4 Summary concerning digital planning models

The three cases related to digital planning models show that nowadays local conditions can be easily aggregated at the national and regional levels. The implication is that areas suitable for district heating can be identified more quickly. This progress can facilitate policy decisions about district heating and company decisions concerning the extension of existing systems and the establishment of new systems.

10.8 AGGREGATED FINDINGS FOR THE VALUE CHAIN

The aggregated findings concerning the cross-cutting possibilities in the value chain are summarised according to the seven strategic possibility groups that were identified in this chapter.

First, emerging possibilities for decarbonisation have more **degrees of freedom** than existing systems that use traditional district heating technologies based on combustion of fuels. These new possibilities should be implemented when extending existing systems and establishing new systems. However, not all substitution possibilities are available everywhere since their availability depends on local conditions. This is an important difference compared to previous generic district heating technologies, which were suitable for applications worldwide. Another key conclusion is that direct heat supply substitution projects for decarbonisation must be supported by other possibilities that increase the overall profitability of the substitution projects by providing a more efficient heat supply.

Second, possibilities concerning using **lower temperature** in heat distribution networks are the leading option for more profitable decarbonisation since most non-fossil heat supply options are more efficient at lower temperatures. A wide range of low-temperature possibilities is available for new systems, whereas existing networks traditionally work with high temperatures. However, several cases have proved that temperatures can be lowered in existing systems by eliminating temperature errors in networks, substations, and customers' heating systems.

Third, possibilities with **heat pumps** indicate that heat pumps are an efficient general tool for overcoming mismatches between supply and demand temperatures in district heating systems. Heat pumps can be implemented when using heat, connecting customers, moving heat, storing heat, recycling heat, and providing heat in linear supply chains from low-temperature sources. However, one challenge is choosing sustainable refrigerants for large heat pumps.

Fourth, possibilities based on **digitalisation** provide opportunities to operate district heating systems closer to the edge with respect to operational stability and safe heat delivery by narrowing current wide operation margins. The digitalisation of district heating has now reached networks, substations, and customers' heating systems. Further digitalisation will increase the operational efficiency of district heating systems since current operations are based on old traditions and guesses about moving heat in heat distribution networks.

Fifth, in some cold distribution networks, **supply responsibility** can be an issue since multiple decentralised heat suppliers tend to dominate the heat supply in these networks. These shared supply responsibilities must be handled by defining the character of each decentralised heat supply. The remuneration level can be set according to the supply character. A large heat storage unit in the heat distribution network can be used as a collective guarantee of heat deliveries.

Sixth, the international and national **institutional frameworks** for district heating provide both support and barriers for district heating activities. On the support side, some national bans on fossil fuel boilers have been introduced. Moreover, national support schemes have appeared in countries with a low market share of district heating. District heating research and development funds promoting decarbonisation have increased in recent years, both nationally and in the EU. On the barrier side, international energy and carbon dioxide accounting rules still do not acknowledge the nature of heat recycling in district heating systems. The European district heating sector is still waiting for appropriate international or national remuneration schemes for carbon dioxide removal from the combustion of biomass and waste.

Seventh, the emerging use of **digital planning models** has facilitated the aggregation of local conditions to national and international levels, providing more accurate advice for the extension of existing district heating systems and the development of new district heating systems.

11 Aggregated conclusions

Based on the three initial research questions in Section 1.3, this inventory of early decarbonisation projects in district heating systems has resulted in the following three major conclusions.

First, **decarbonisation activities** can be divided into substituting and supporting possibilities. **Substituting possibilities** in heat supply include linear supply from renewables, heat recycling from processes that generate excess heat, and non-fossil ways of meeting peak heat demands during very cold days. The linear heat supply is based on geothermal heat, solar heat, and electricity supply. Heat recycling is possible from various processes related to biorefineries, hydrogen supply, petrochemical plants, electricity distribution, district cooling, data centres, battery factories, food supply chains, and sewage waters. Heat storage can make heat delivery more independent of heat supply and provide additional opportunities to reduce peak loads. **Supporting possibilities** mainly comprise activities for obtaining lower temperatures in heat distribution networks to increase profitability when using low-temperature heat sources. These activities are performed when connecting customers, moving heat, and using heat. Another supporting activity is the removal of biogenic carbon dioxide from the natural carbon cycle, although an appropriate international accounting system for its removal is still missing.

Second, the **decarbonisation possibilities** of district heating systems differ from those of traditional systems based on fossil fuels. The availability of decarbonisation possibilities for district heating depends on local conditions, whereas fossil fuels are transported from available global resources and are used worldwide. Hereby, decarbonised district heating systems will not be as uniform as traditional systems based on fossil fuels. The local conditions lower the degrees of freedom for the implementation of substituting possibilities in existing buildings and systems. Hence, it is important to adopt new methods for utilising the highest degree of freedom possible in new buildings and systems.

Third, the **common denominators** for the 70 identified possibilities are degrees of freedom for decarbonisation, action plans for achieving lower heat distribution temperatures, the use of heat pumps for upgrading low-temperature supplies to meet high-temperature demands, smart digitalisation options, clear supply responsibilities, favourable institutional frameworks, and digital planning models. These seven common denominators are efficient tools for obtaining decarbonised and more efficient district heating systems in the future. These redesigned and new systems will be somewhat different than traditional systems, which have been based on a district heating technology that was originally elaborated for systems based on fossil fuels.

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13 Location index

In this location index, all locations having identified cases in this report are listed with information about what page/pages where these cases can be found.

70 NEW POSSIBILITIES FOR DISTRICT HEATING

This report contains the results from an inventory performed during 2022 and 2023 of early initiatives for decarbonisation of district heating systems. It is structured by identification of 70 possibilities and supported by 284 implemented, planned, or proposed cases from Europe, North America, and China. The three main conclusions are (1) decarbonisation activities can be divided into substituting and supporting possibilities, (2) the availability of decarbonisation possibilities depend on local conditions, and (3) the seven common denominators for these possibilities are degrees of freedom for decarbonisation, action plans for getting lower heat distribution temperatures, various ways of using heat pumps for upgrading low supply temperatures for satisfying higher demand temperatures, smart digitalisation options, clear supply responsibilities, favourable institutional frameworks, and digital planning models.

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