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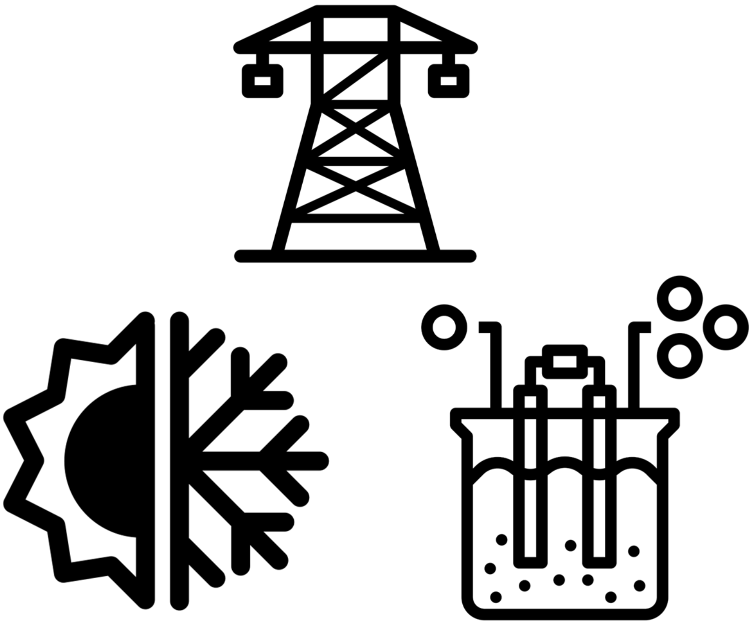

IEA DHC ANNEX TS3: HYBRID ENERGY NETWORKS

APPENDIX A
LARGE-SCALE HEAT PUMPS IN DISTRICT HEATING NETWORKS

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CONTENT

1 INTRODUCTION

This Appendix is part of the IEA DHC Annex TS3 guidebook. The full guidebook is available at https://www.iea-dhc.org/the-research/annexes/2017-2021-annex-ts3

Author: Daniel Trier

LARGE-SCALE HEAT PUMPS IN DISTRICT HEATING NETWORKS

IEA DHC ANNEX TS3 – HYBRID ENERGY NETWORKS

Author: Daniel Trier

PlanEnergi
Nørregade 13, 1st fl.
1165 Copenhagen K
Denmark

10-02-2023

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Introduction

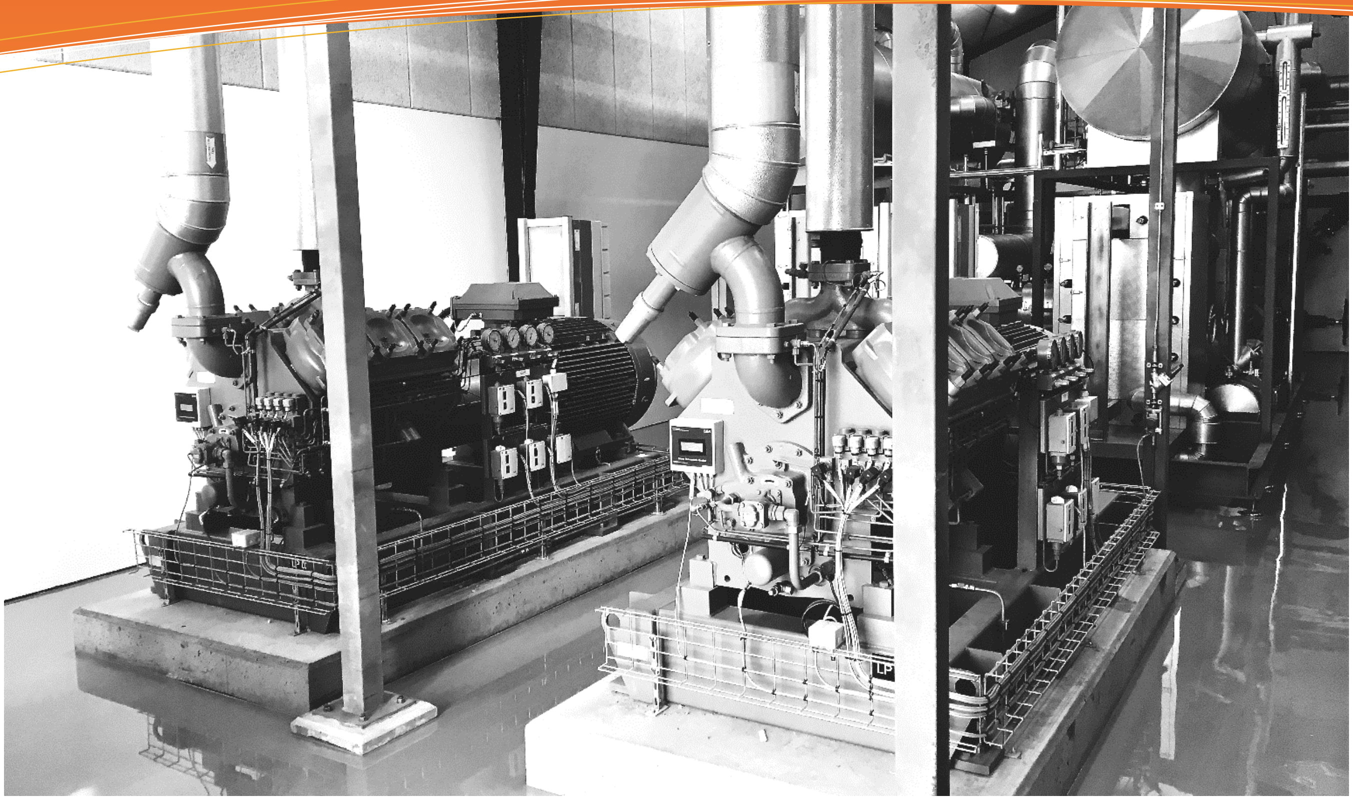
The following sections can be addressed separately and considered standalone documents. They are developed within the IEA DHC TS3 “Hybrid Energy Networks”, subtask A “Technologies and synergy potential”, WP2 “Experiences with hybrid energy networks based on large-scale heat pumps”.

The selected key topics introduce the subject of large-scale heat pumps for district heating. The content is based on the latest practical experiences from their current deployment seen in the Danish district heating system. The aim is to direct information to relevant stakeholders such as decision-makers, authorities, utilities and others interested in how heat pumps for district heating can create links between the electricity and heating sectors thus representing “hybrid” energy networks and systems. Since various other relevant sources of information exist covering case studies and the thermodynamic principles of the technology these topics are not included here. Further information is available at the homepage for the IEA Technology Collaboration Programme on Heat Pumping Technologies (IEA HTP): heatpumpingtechnologies.org.

The standalone documents cover the following topics:

- Market status, incentives and policies in Denmark
- Configurations and energy system integration
- Heat sources
- Refrigerants
- Air-source heat pump operation
- Tendering process
- Economics and the electricity grid connection

LARGE-SCALE HEAT PUMPS IN DISTRICT HEATING NETWORKS



MARKET STATUS, INCENTIVES AND POLICIES IN DENMARK

IEA DHC ANNEX TS3 – HYBRID ENERGY NETWORKS

Technical Report of the IEA DHC TS3 “Hybrid Energy Networks”, subtask A “Technologies and synergy potential”, WP2 “Experiences with hybrid energy networks based on large-scale heat pumps”: *Market status, incentives and policies in Denmark*.

Author: Daniel Trier

PlanEnergi
Nørregade 13, 1st fl.
1165 Copenhagen K
Denmark

10-02-2023

Content

1 Danish market for heat pumps in district heating

1.1 Market development

The website www.heatpumpdata.eu contains a map showing the location of all known large-scale heat pumps connected to district heating networks in Denmark together with an associated list. Each heat pump icon has its main properties stated in an info box such as rated themal power, type of heat souce, commissioning year etc. The list and map are updated regularly to include the latest heat pumps commissioned.

Figure 1 shows the development of district heating heat pump capacities in Denmark until end of 2022. There was a significant increase of these capacities during 2020 due to an incentive scheme ending by the end of the same year as described in section 2.1.

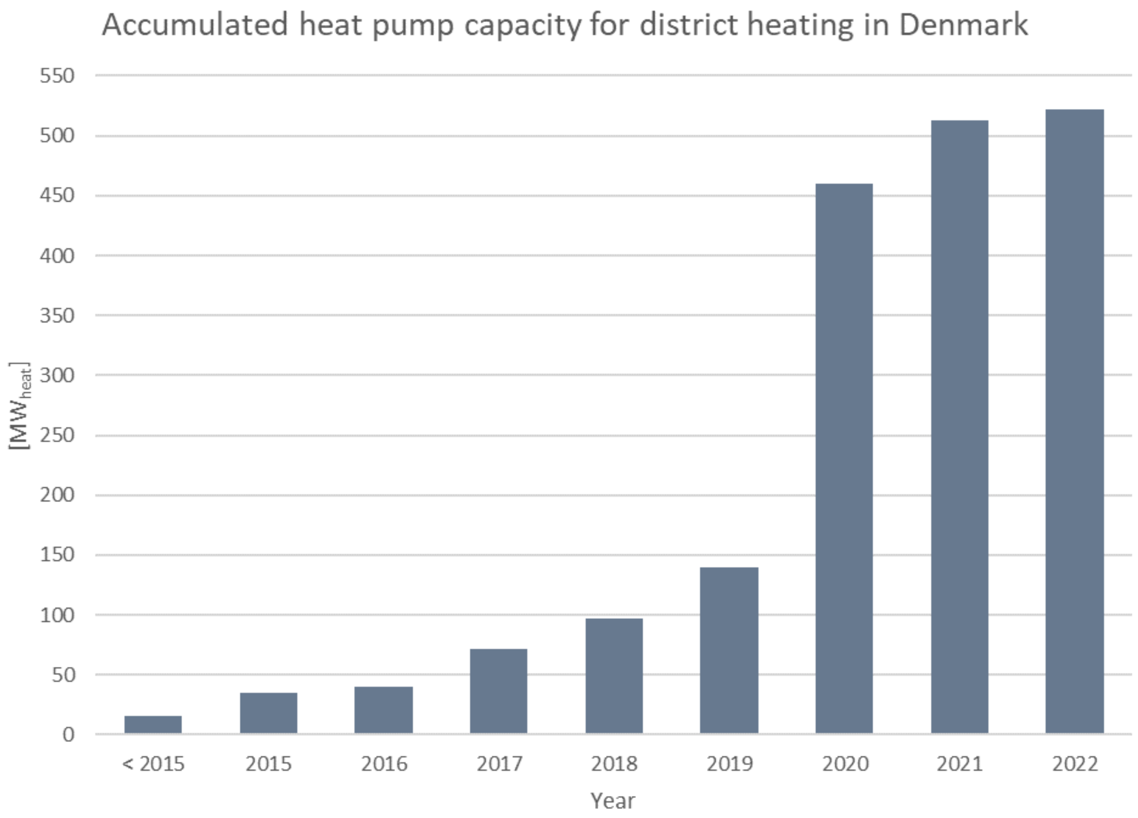


Figure 1. Accumulated heat pump capacity (heating) for district heating in Denmark.

1.2 Heat source trends

Both in terms of thermal capacity and number of systems, more than half of the installed heat pump systems are air-source heat pumps as seen in Figure 2.

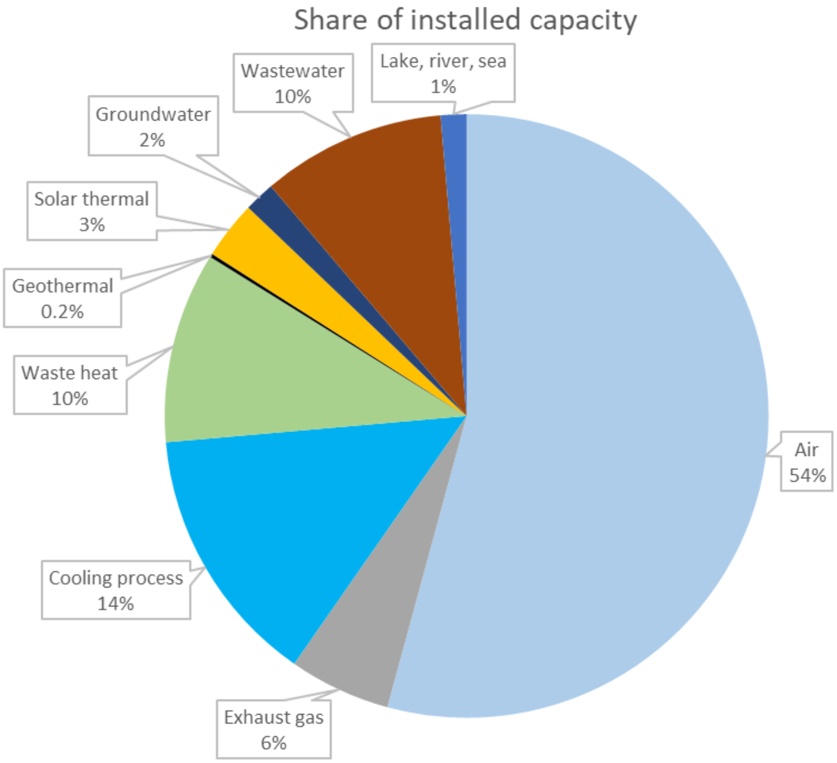


Figure 2. Share of installed heat pump (heating) capacity for district heating.

The difference between the category "cooling process" and "waste heat" is that the cooling process implies an active demand for cooling whereas waste heat would if unused alternatively simply be discarded to the environment without any (or almost any) energy required to do so. One example of a cooling processes in this respect is district cooling supply where the condenser side of the heat pump is used for district heating and the evaporator side is supplying district cooling. Another example is data centres.

A different way to indicate the market share of heat pumps in district heating is by the number of heat pump systems installed as seen in Figure 3. It is seen that in general the ratio levels are somewhat similar to the installed heat pump capacity in Figure 2. However, the typically relatively small exhaust air heat pumps cover a larger share when it comes to the number of installed heat pump systems.

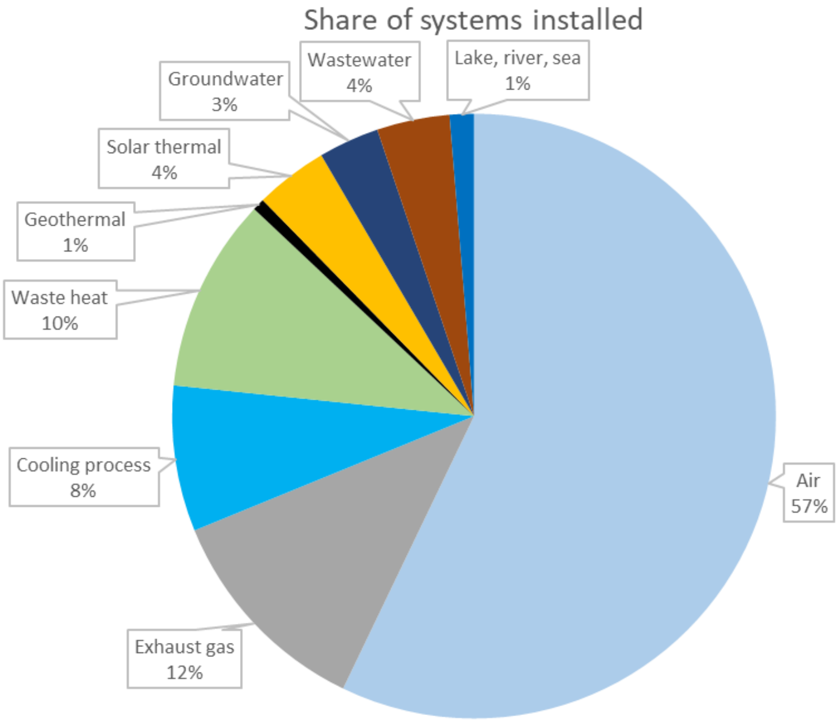


Figure 3. Share of heat pump units by (main) heat source.

1.3 Heat pump capacities

To compare the sizes of systems, the average and maximum size of the heat pumps are illustrated in Figure 4. The largest number of air-source heat pumps on average have a nominal capacity of 3.2 MW (heat output). Waste heat systems are on average at 3.3 MW, cooling processes at 6.1 MW, exhaust gas at 1.6 MW, and wastewater heat pumps at 8.6 MW. In many cases small towns have been leading the way for the use of heat pumps for district heating. However, there are also cities taking part in the development representing a potential for larger scale heat pumps in the future. Currently there are a number of systems planned at city scale e.g. a 50 MW sea water heat pump in Esbjerg. The availability of various heat source options is often higher in a big city compared to a small town and the connection to the network using a transmission line represents a relatively small share of the overall heat pump system costs. Compared to Figure 3, a more diverse heat source distribution is expected in the coming years.

The heat pump size does not follow a certain capacity-to-population ratio. By investing in several heat pumps instead of one big system – possibly using different heat sources – the utility can reduce its risks by being less dependent on a specific technology and the supply of that specific heat source (e.g. weather conditions for air or amount of wastewater).

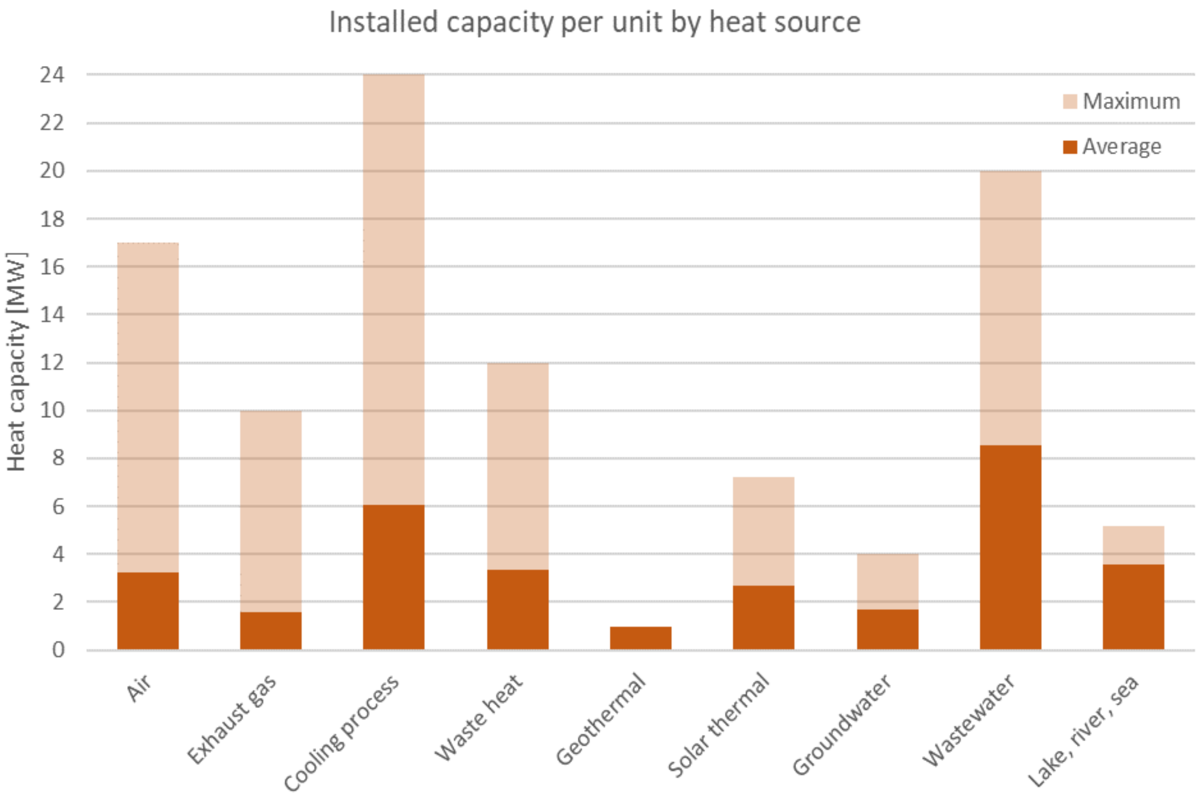


Figure 4. Average and maximum heat capacity per heat pump unit by (main) heat source.

2 Policies and incentives

2.1 Overview of measures promoting large scale heat pumps

Denmark is one of the countries with the highest share of wind power compared to the electricity demand. The electrification of a range of demand categories (residential heating, industry, transport etc.) is politically a priority as a means to replace fossil fuel use with renewable energy in order to reach the national target to become carbon neutral by the year 2045. District heating presents an opportunity to convert entire towns and cities by changing the centralised heat supply without the need for individual households to invest or engage in a new heating unit. Financial support for investments in large scale heat pumps have been granted in several ways over the past few years.

The figure below shows two key support categories implemented in Denmark to promote the use of heat pumps in district heating.

Knowledge support

2015-2018: The Danish Energy Agency's own traveling experts team visits the DH plants to discuss opportunities and providing advice on heat pump options for free. Experienced from cases are gathered and shared.

2019-2023: Smaller DH plants can apply for free consultancy services to investigate how to lower prices. Public funding ensured professional advice from a consortium of experienced companies.

The Danish Energy Agency supports the participation in several heat pump research projects through the "Energy Technology Development and Demonstration Programme (EUDP)" (continuous).

The Danish District Heating Association facilitates the sharing of practical experiences by organising knowledge sharing groups (networks). Since 2020 one group has been dedicated to heat pumps.

Financial support

2017-2018: Investment support to promote and showcase heat pump for DH as a viable option.

2017-2020: The installation of HP in DH created energy savings credits which could be sold on an associated credit stock market thus representing up to 20% of the HP investment cost.

2018-2023: Substantial reduction of electricity taxes (several times) – initially targeting only electric heating solutions, lately in general.

2020-2023: Investment support for DH plants replacing fossil fuels. Funding prioritized in order of most CO_2 displaced per DKK. Possible grant: 15-30% (2021/2022) provided that 50%/25% (2021/2022) of DH supply is fossil fuel-based.

Figure 5. Knowledge and financial support mechanisms for large scale heat pumps in Denmark.

In terms of the energy savings credits mentioned in Figure 5, district heating was part of a cross-sectoral political agreement on energy savings between the government and the grid and distribution companies for electricity, natural gas, district heating and oil[1]. The agreement meant that all sectors were obliged to realise a certain amount of savings each year. Realised savings created credits which could be sold on a dedicated stock market by those who created more than needed to those who did not themselves achieve their required savings. Heat pumps in district heating would create credits according to the production during one year of operation minus the associated energy demand.

Key stakeholder organisations were interested to enter such an agreement since they preferred to have their say in the wording of such an agreement rather than being forced by law to comply with restrictions developed without their inputs.

The setup was attractive enough for the supply of credits at some point to result in credit prices close to zero. This credit market uncertainty did not discourage investments in heat pumps and the end of the agreement resulted in a rush to commission heat pumps before the deadline at the end of 2020.

There were also other indirect incentives such as the taxation of fossil fuel alternatives. Similarly, the extension of the district heating coverage is politically regarded as an important measure to replace fossil fuels with sustainable heating. Public funding to support the conversion from natural gas to district heating has been granted. This increases the demand thus also extending the market potential for large scale heat pumps.

2.2 The incentive dilemma

The political decision to promote heat pumps by lowering electricity taxes/tariffs reveals an “incentive dilemma” where lowering electricity taxes to improve the feasibility of heat pumps also reduces the incentive to improve the performance of heat pumps (COP) (relatively) thereby indirectly somehow favouring less efficient solutions. On the other hand, and the use of heat pumps replacing fossil fuels is an effective way to reduce GHG emissions in general. Another parameter in the equation is *when* the electricity is used, which affects the electricity’s carbon footprint. With a growing share of variable RES, the energy system requires an intelligent interaction with the electricity grid rather than non-flexible electricity consumption. Larger variation in tariffs across the day and seasons – on top of the variable spot prices – can be used to divert electricity use away from peak load

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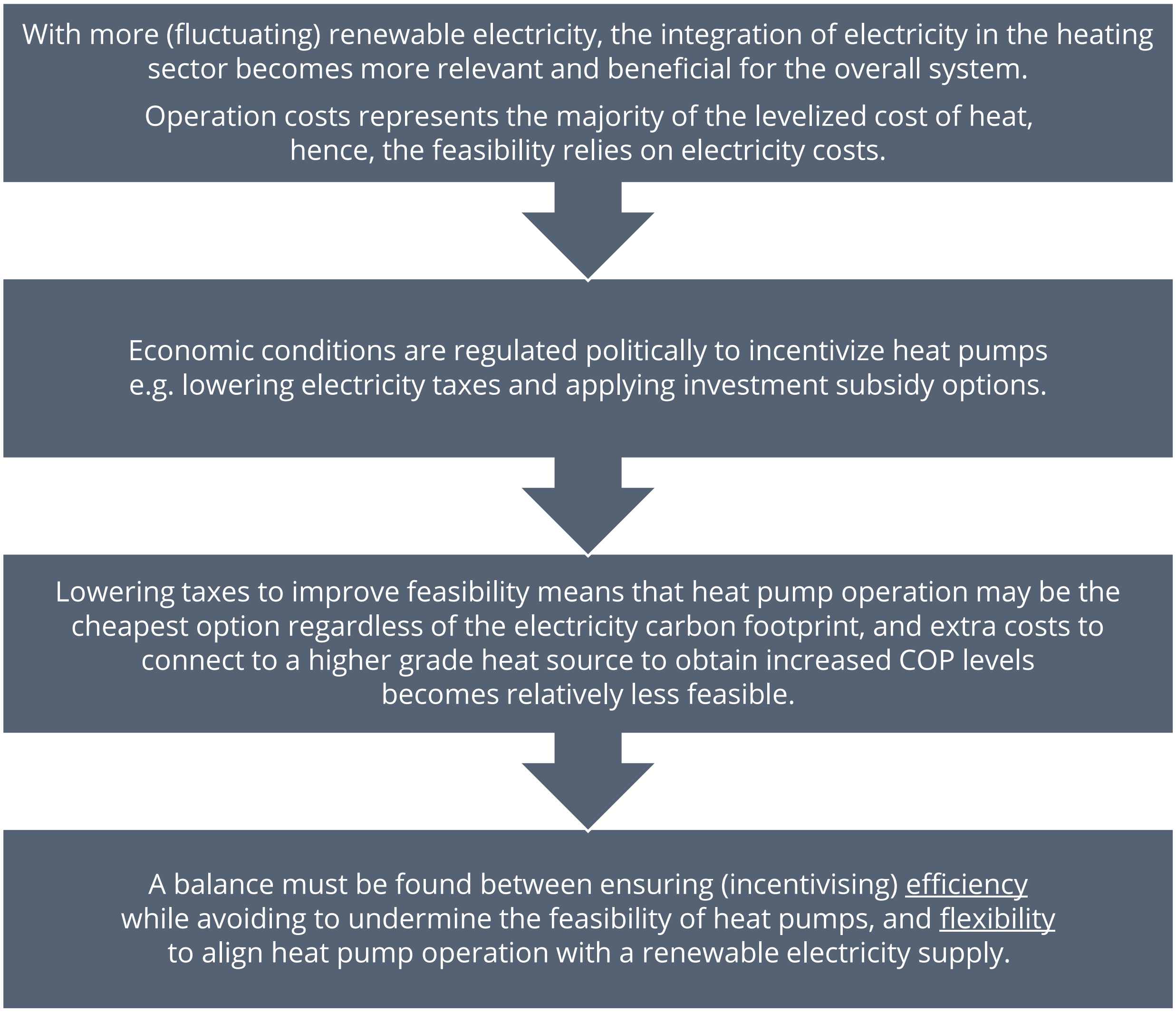
[1] The original 2012 agreement text (English) can be downloaded at energy.ec.europa.eu/document/download/a994940a-bd8e-4b26-b7a4-0f5d303b5f11_en?filename=article7_en_denmark_annex-a.pdf and the 2016 update (in Danish) at ens.dk/sites/ens.dk/files/Energibesparelser/bilag_5_-_energispareaftale_2016.pdf.

hours. Such diversification of tariffs has recently been applied to an increased extent over the day, week, and seasons.

In terms of the political “incentive dilemma” between lowering operation costs and incentivising efficient operation, a stepwise process can be derived:



With more (fluctuating) renewable electricity, the integration of electricity in the heating sector becomes more relevant and beneficial for the overall system.

Operation costs represents the majority of the levelized cost of heat, hence, the feasibility relies on electricity costs.

Economic conditions are regulated politically to incentivize heat pumps e.g. lowering electricity taxes and applying investment subsidy options.

Lowering taxes to improve feasibility means that heat pump operation may be the cheapest option regardless of the electricity carbon footprint, and extra costs to connect to a higher grade heat source to obtain increased COP levels becomes relatively less feasible.

A balance must be found between ensuring (incentivising) efficiency while avoiding to undermine the feasibility of heat pumps, and flexibility to align heat pump operation with a renewable electricity supply.

Figure 6. The promotion of heat pumps reveals an “incentive dilemma” between lowering operation costs and incentivising efficient operation.

3 Renewable energy fuels for district heating

Some alternative options for producing heat throughout the year are boilers or CHPs. The options to ensure sustainability and alignment with national and international climate targetsinvolve the use of synthetic fuels (e.g. green hydrogen or a product based on it) and biomass/biogas. The use of these – including the option to use biogas and green hydrogen as a direct replacement for fossil methane (natural gas) – comes with significant limitations and other drawbacks.

3.1 Biomass

A substantial share of the current renewable energy supply in Denmark consists of biomass. Though certification schemes are put in place to avoid deforestation e.g. in Brazilian rain forests, and there is a focus on the use of waste wood when it comes to wood pellets/chips, the role of biomass as a means to a renewable energy transition is not simply replicable in all countries – mainly due to the scarcity and future demand of biomass in other hard-to-abate sectors such as heavy transport and industry. As indicated in the International Renewable Energy Agency (IRENA) publication "Bioenergy for the Transition: Ensuring Sustainability and Overcoming Barriers", different key stakeholder organisations estimate the biomass supply by 2050 to be between 40 and 250 EJ per year with IRENA itself stating around 150 EJ."[2] With 8-10 billion people globally 100-150 EJ corresponds roughly to around 15 GJ/person annually. To put things in perspective, this (only) corresponds to the heating value contained in approx. two straw bales of 500 kg. This illustrates how the use of biomass is not expected to be suited as widely used baseload option for the future of district heating.

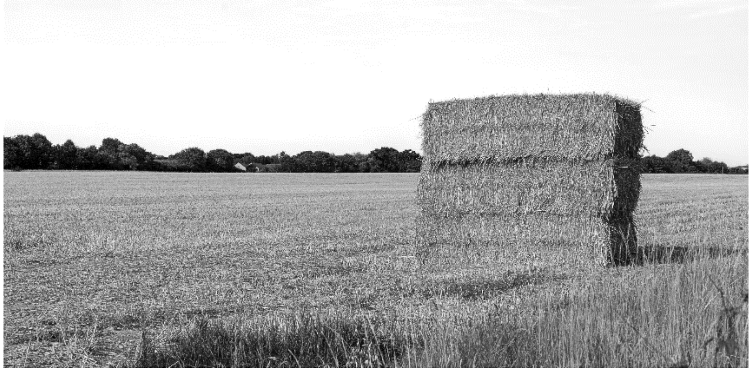


Figure 7. If the biomass resources are to be shared evenly, there will only be enough for a couple of straw bales similar to the ones in the picture per person each year.

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[2] IRENA: 153 EJ of biomass supply by 2050. IEA: Likely 130-240 EJ. IPBES/IPCC: 50-90 EJ. The Energy Transition Commission: 40-120 EJ. www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Aug/IRENA_Bioenergy_for_the_transition_2022.pdf?rev=875a997481f04168b17499f1e5dc1473.

3.2 Hydrogen for heating

Hydrogen boilers are highly inefficient compared to heat pumps and even in a 100% RE-based energy system where the hydrogen is considered green, it would require a substantial amount of extra RE capacity to generate the extra energy required to supply hydrogen boilers compared to heat pumps. Even if it is obtainable in practice, it would result in additional costs, additional efforts and a missed opportunity to displace fossil fuels elsewhere with the hydrogen wasted in inefficient boilers where the final energy demand is warm water/space heating. Hydrogen can play a role in stabilizing the energy system in periods of the so-called “dunkelfaute” (cold night-time periods with no wind) but should not be used for baseload heating. It should be mentioned that hydrogen may not be used in tis pure form, but in green fuels such as upgraded biomethane, methanol etc. Figure 8 below illustrates an example of scale between using wind power to generate hydrogen for heating or to power heat pumps. Though the exact numbers may not be representative everywhere, the figure indicates the obvious disadvantage of relying on a system using only hydrogen for heating.

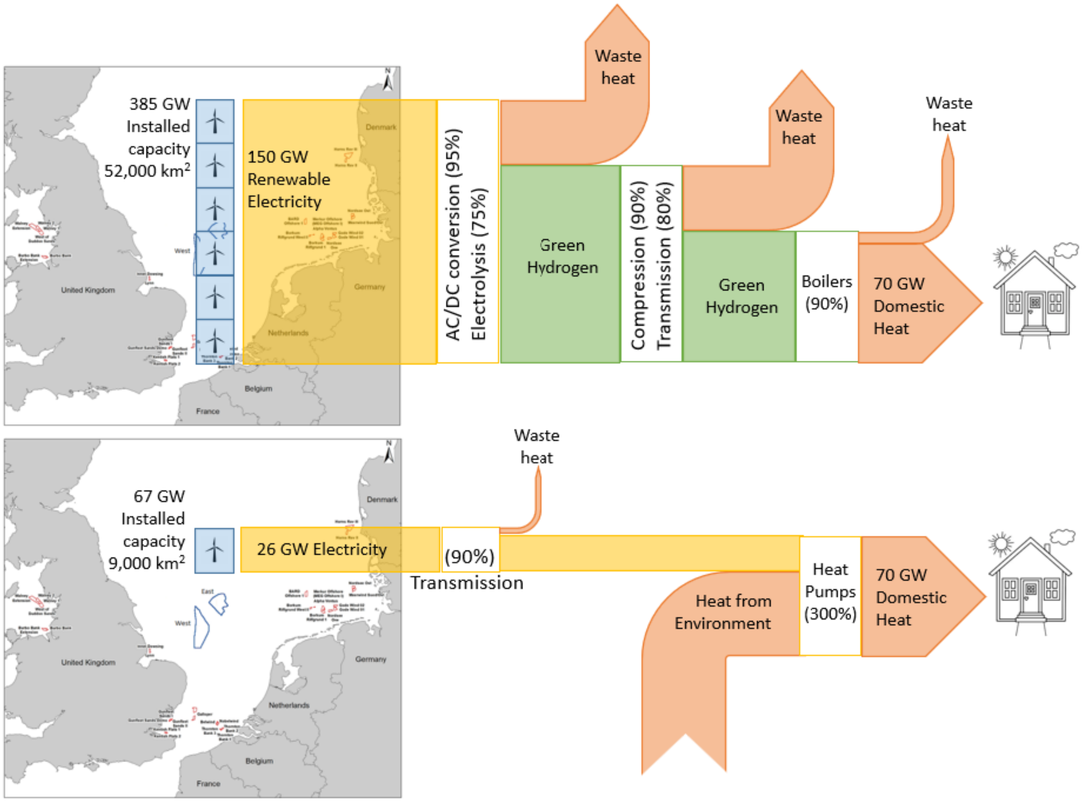

Figure 8. Comparison between hydrogen and heat pumps for heating from the "Briefing on the Energy” Bill by Hydrogen Science Coalition 28/8 2022, https://t.co/ib6LoQEdNW.

CONFIGURATIONS AND ENERGY SYSTEM INTEGRATION

Technical Report of the IEA DHC TS3 "Hybrid Energy Networks", subtask A "Technologies and synergy potential", WP2 "Experiences with hybrid energy networks based on large-scale heat pumps": *Configurations and energy system integration*.

Author: Daniel Trier

PlanEnergi
Nørregade 13, 1st fl.
1165 Copenhagen K
Denmark

10-02-2023

Content

1 Energy system perspective

Heat pumps are expected to play a key role in the future heating supply and thereby the decarbonisation of the overall energy system where heating represents as much as half of the energy demand[1]. The share of heat demand, which could feasibly be covered by district heating (DH) is identified for a range of countries[2], thus also indicating a vast untapped potential for large-scale heat pumps.

Heat pumps enable the integration of (renewable) electricity in the heating sector, and through the DH network they form a "hybrid energy system". An illustration of the synergies between DH networks, heat pumps and energy savings is seen in Figure 1.

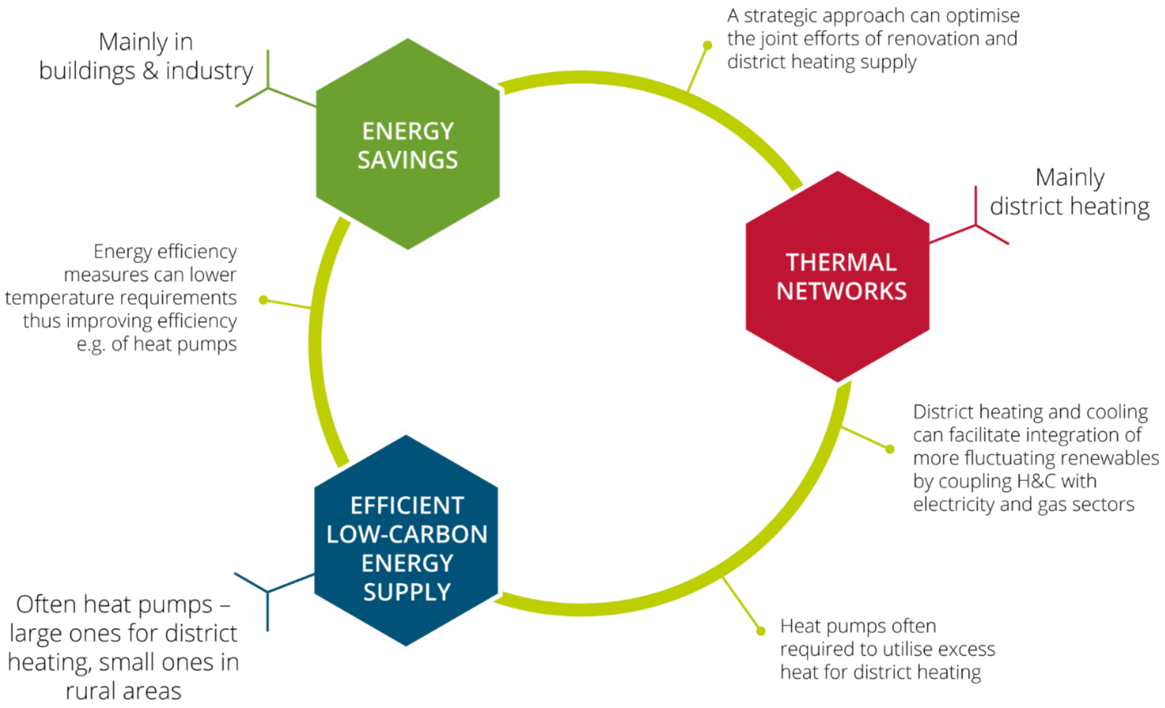

Figure 1. Synergies between selected decarbonisation options (from The Legacy of Heat Roadmap Europe brochure, heatroadmap.eu/legacy-brochure).

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[1] As described in "Profile of heating and cooling demand in 2015", heatroadmap.eu/wp-content/uploads/2018/11/HRE4_D3.1.pdf.

[2] See reports from the Heat Roadmap Europe project on country level at heatroadmap.eu/roadmaps or summarized in the joint report "Towards a decarbonised heating and cooling sector in Europe – Unlocking the potential of energy efficiency and district energy" available at heatroadmap.eu/decarbonised-hc-report.

When considering the feasibility of renovations and energy savings, the value is often considered to be represented by a decreased heat demand – potentially with the addition of extra comfort for the inhabitants. In DH networks, renovations and upgrading the pipes are similarly considered a means to reduce heat losses. However, for both buildings and DH network, renovations often result in lower required temperature levels. While the savings in the energy demand and reduction of losses are significant, the additional benefit for the heat pump should also be considered. A lower forward temperature in the DH network leads to an improvement of the efficiency of heat pumps. This effect should be taken into account when evaluating the feasibility of renovation measures. Such mutual benefits for both DH companies, building owners, and authorities (often representing general emission reduction targets), could be evaluated as part of a strategic partnership between all relevant local stakeholders in a common decarbonisation strategy[3].

2 Configurations

Heat pump configuration

Figure 2 illustrates an example of a heat source cooled from 40 °C to 15 °C while the DH supply is heated from 60 °C to 90 °C. The numbers are simply examples while the DH temperature levels are typically lower in Danish DH systems (often around 70-75 °C forward temperature).

In comparison, the process could be split in several sub-processes, each representing part of the total needed temperature increase and heat transfer. The final temperature increase to reach the DH forward temperature is then the *last* step seen from the DH water perspective whereas it is the *first* step for the cooling circuit (where the heat source temperature is highest). This energy transfer link in this process is illustrated with a dark green arrow in Figure 3. Correspondingly, the final step at the end of the cooling circuit cycle is raising the DH temperature from its return water level as is indicated in Figure 3 with the brightest arrow.

Such a stepwise configuration connecting processes operating in series enables significantly higher COP levels. The chosen configuration of a heat pump is therefore a key point to obtain an efficient system.

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[3] Further information on this topic can be found in “Guidelines for the Energy System Transition – Recommendations for Local and Regional Policymakers” available at heatroadmap.eu/project-reports.

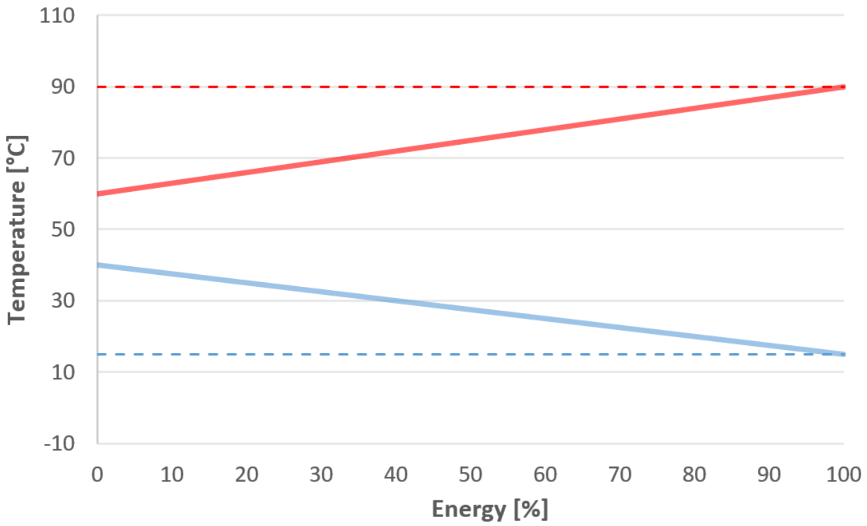

Figure 2. Example of temperature development for a heat pump associated with the energy transfer. The heat pump supplies DH at a temperature indicated with dashed red. The DH water temperature is indicated in full red. The heat source is cooled down to the dashed blue level in the process shown with a blue line.

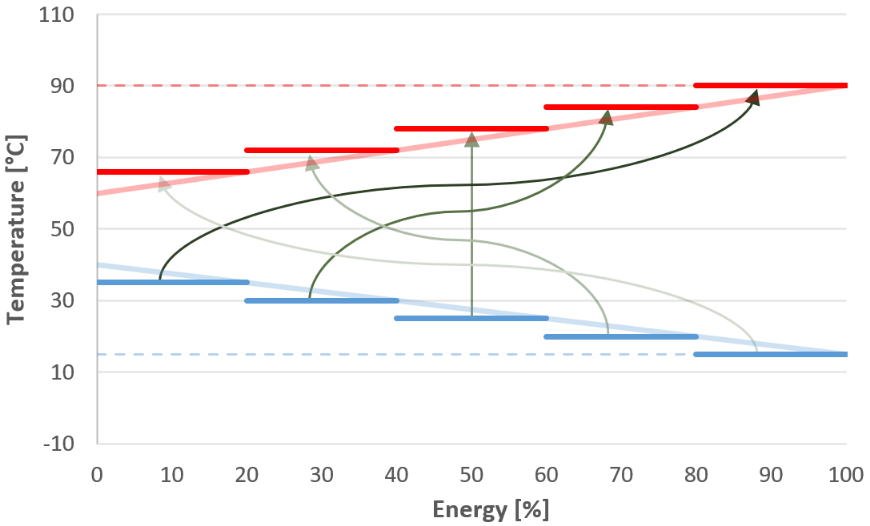

Figure 3. Example of temperature development for a heat pump associated with the energy transfer when split in five sub-processes each representing part of the heat exchange and temperature increase/reduction. Heat source temperatures are seen in blue, DH temperatures in red and connections between each of the five processes are illustrated with green arrows.

2.1 Design optimization – investment choices

Complex systems provide an opportunity to maximize the COP, but in turn include a larger number of potential component failure points. The stability of the chosen solution is increasingly important when the heat pump plays a main role in the DH company's energy mix. Electricity costs – even with less-than-ideal COP levels – may be manageable, while longer periods of downtime can be extremely costly due to the use of expensive backup production capacity. However, a less practical risk involved in aiming for a cheaper, simpler solution is the uncertainty of future electricity prices and the impact of unforeseen events causing periods of extreme electricity prices. A more efficient system will be more resilient based on the lower electricity demand while the down payments on the loan for the investment can remain fixed.

The trade-off between efficiency and investment costs is a critical point when choosing the most suitable heat pump solution for a given case. The range of investment costs for a given thermal capacity can be significant, representing additional cost to achieve higher efficiency. Hence, the expected future electricity price becomes an important parameter in this respect – and not only when comparing heat pumps to other production capacity options.

Presuming the decision is made to invest in a heat pump with a selected heat source to cover a certain share of the heating demand, a comparison to consider involves two different approaches for a given project – even if the total investment costs are similar:

A. A certain heat pump capacity operating at high COP levels to minimize operation costs.
B. Extra heat pump capacity in a simpler setup compared to option A – which in turn entails a lower COP – combined with (extra) thermal storage capacity. The extra capacity enables the operator to produce extra heat (and store it) in periods with the lowest electricity prices/carbon footprint.

The extra production and storage capacity of option B – together with a potentially more agile system accepting quick ramping up/down – may represent additional flexibility, which could compensate for the lower efficiency. However, the majority of flexibility may be obtained by a thermal storage thus representing an ideal mix between efficient operation *and* flexibility. There is not one "right" answer and the best solution in a given case is also affected by the options for integrating the heat pump with the remaining production units. More information on evaluation can be found in the document "Tendering process".

2.2 Storages

In many cases, new or additional short-term storage capacity to cover several hours (or up to a few days) represents valuable flexibility and stability for the system. A storage enables the optimization of the heat production by utilizing the hours with the lowest electricity prices and making it possible to avoid operation during electricity peak load hours.

A variety of sensors check that the conditions for normal operation of the heat pump is met. In case the temperature fed to the heat pump at the condenser side (i.e., at the DH return water temperature) fluctuates too much – in case of swift variations in the DH demand – a heat pump outage may occur. A storage acting as a buffer between the heat pump operation and DH demand can help ensure stable operation conditions.

The points mentioned above are especially important in DH plants where one heat pump covers most of the heat demand. It is generally recommendable to consider the option of adding a thermal storage feature in a large-scale heat pump investment.

2.3 Connection to other production units

The integration of heat pumps in the DH plant is not simply a matter of space and practicalities but can result in significant additional value associated with the operation strategy. The chosen connection points define what options are later available in terms of combining different production units. Since the COP is affected by the required supply temperature, it should be analysed to which extent the heat pump is expected to operate in connection with other units and how the desired operation strategies can be realised in practice (based on piping, valves, and connection point). The combined operation when the heat pump cannot cover the demand by itself can be done in parallel or in series:

I. Standard parallel operation where each unit received the DH return temperature and delivers the DH forward temperature (non-optimised.)
II. Series connection where the heat pump is used to increase from the DH return level to an intermediate temperature (optimized).
III. Series connection where other units deliver the first temperature increase feeding this to the heat pump, which then supplies the remaining temperature lift (often not ideal).

Option I above indicates the most simple operation since the different production units can operate independently. Option II requires a more complex control where the temperature settings must be aligned with the flow rates, which also may be limited in some units. In this case a storage can act as a buffer applying stability to the operation.

Option III is typically not relevant since the heat pump will benefit from lower temperatures while for example boiler operation is less affected. However, with the combination of solar thermal systems, there are periods where the system efficiency will benefit from this setup though these periods are in general limited.

One option is also to apply a parallel connection where the temperature levels are adjusted to minimise the outlet temperature from the heat pump by shunting the output flow with a higher temperature e.g., from a boiler. In any case the overall efficiency of the system should be evaluated rather than considering each unit separately.

2.4 Self-supply of electricity

There is an increasing interest from DH companies regarding the installation of solar PV and wind turbines close to large-scale heat pumps in order to apply a direct connection between the units. The reduced cost of renewable electricity represents a relevant business case for many DH companies. At the same time, the solution represents a reduced dependency of fluctuating electricity prices thus making the DH company and associated heat prices more resilient. The latter has shown to be of increased importance during 2022. It also ensures a 100% renewable electricity supply for the share covered by the PV system or wind turbine. Local and/or national legislation may, however, limit the potential number or size of such production. The ability to produce electricity as a DH company mainly to use in a heat pump but also to sell to the grid underlines the generational change in Danish decentralised DH plants, formerly relying heavily on CHP based on natural gas, while in the future primarily acting as electricity consumer though with the ability still to supply electricity to the grid by means of CHP units and possibly PV/wind when the prices are high. The direct connection and the ability to optimise the use/sale of produced electricity increases the feasibility of thermal storage as described in section 2.2.

HEAT SOURCES

Technical Report of the IEA DHC TS3 “Hybrid Energy Networks”, subtask A “Technologies and synergy potential”, WP2 “Experiences with hybrid energy networks based on large-scale heat pumps”: *Heat sources*.

Authors: Daniel Trier,
Magdalena Komoszynska
and Matteo Daminato

PlanEnergi
Nørregade 13, 1st fl.
1165 Copenhagen K
Denmark

10-02-2023

Content

1 Heat source overview

When considering heat pump options, an initial screening of the relevant heat source alternatives is necessary. To compare the advantages, disadvantages, and feasibility of available options, a first step can be to address the flow chart in Figure 1 and the overview in the following sections. In general, the highest temperature heat source can enable the highest COP levels and thereby the least electricity use per unit of supplied heat. Local conditions can influence the stepwise approach, but the figure can illustrate the idea of considering various options before choosing a specific solution. Though the efficiency using other sources is in general higher, air has in many cases proven to be the chosen/available heat source in the end as indicated in the document “Market status, incentives and policies in Denmark”.

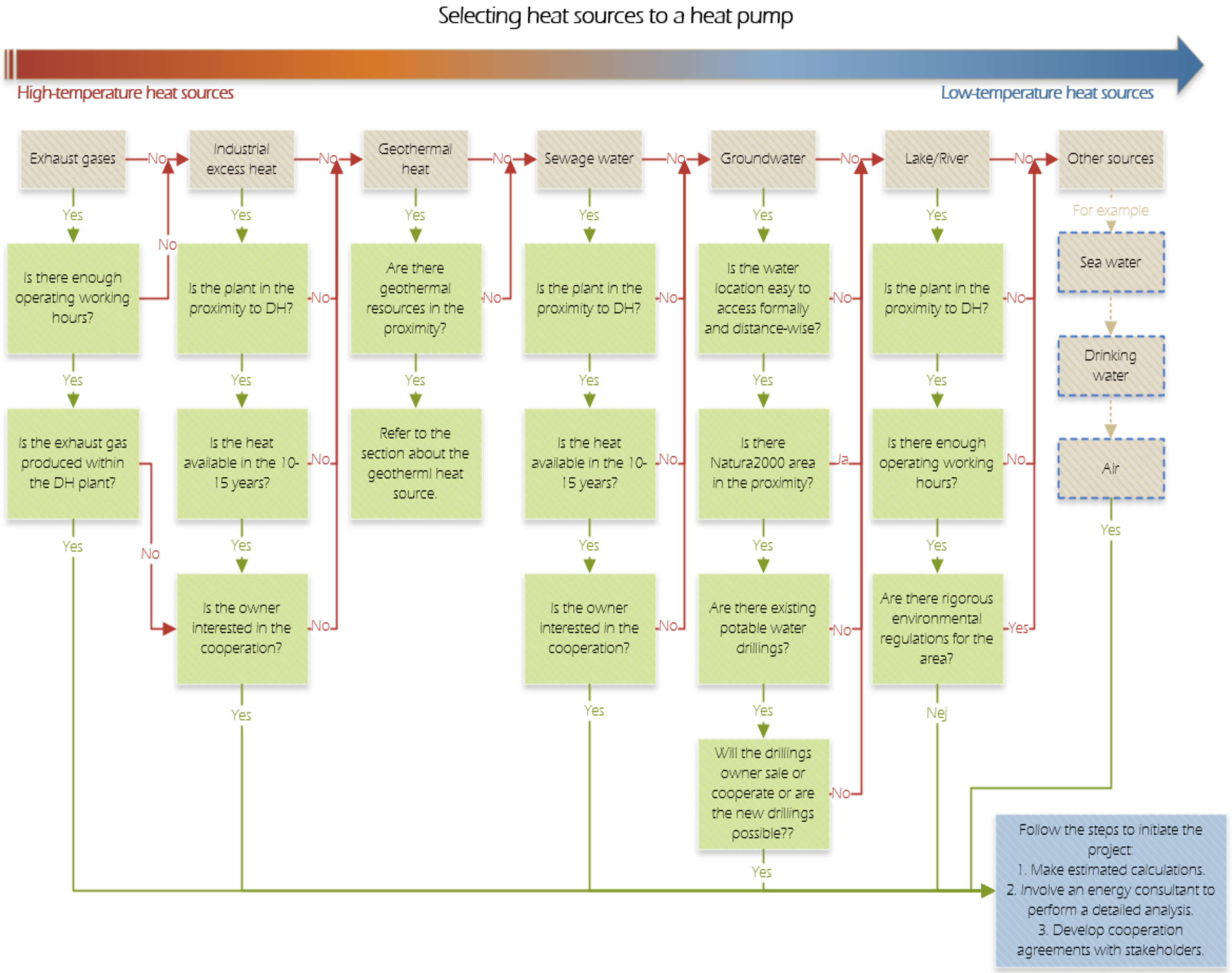

Figure 1. Heat source selection flow chart.

2 Strength and weaknesses of different options

In the following section, advantages and disadvantages of the heat sources indicated in Figure 1[1] are listed.

2.1 Exhaust gases

Every exhaust gas (or flue gas) produced by combustion of a fuel (fossil or non-fossil) can be cooled down before being led out to the surrounding environment. If the flue gas is warmer than the return temperature of the DH network, it can be used to warm up the water directly (using a heat exchanger). When the temperature of the flue gas is below the return temperature, a heat pumps is required to extract the heat.

Temperature:

Temperature levels can range from approximately 50 °C up to more than 100 °C.

Advantages:

- Relatively low-cost unit and installation compared to heat pumps with other heat sources.

Disadvantages:

- Flue gas condensation contains pollutants, that must be contained and disposed properly if it cannot be party/completely neutralized and diverted to the sewer. This entails a cost that must be considered in the feasibility of the solution.
- The heat pump operation is linked with the operation of a fuel-based device. The heat pump will only be able to recover 5-10% of the energy from the flue gas, which limits the savings potential.

2.2 Industrial excess heat

Excess heat can be retrieved from the industry, including chemical processes, food production and from data centres. An increasing number of data centres are built, and it can be useful to initiate an early dialogue with the owners to investigate the option of installing equipment preparing the excess heat utilization already during the data centre construction phase. In case water cooling of servers is implemented, the extraction of heat to be used for DH is more straightforward and efficient, but this is not a necessity for utilizing data centre heat as a source.

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[1] A source of information involves the gathered experiences described in the Danish “Drejebog til store varmepumpeprojekter i fjernvarmesystemet” (guidebook for large-scale heat pump projects in the district heating system) from December 2017.

Regarding agreements between the DH company and industries a list of topics is found in the document "Tendering process".

Temperature:
The heat can be utilized in three different ways, depending on the temperature level and the requirement of the specific DH network:

- High temperature: Direct heat exchange without the use of heat pumps (e.g., excess heat cooled from 95 °C to 40 °C, while DH is heated from 35 °C to 75 °C).
- Medium temperature: A combination of direct heat exchange and utilization of a heat pump is possible (e.g., excess heat cooled off from 55 °C to 25 °C using direct heat exchange as the first step and a heat pump as a second step, while the DH is heated from 35 °C to 75 °C).
- Low temperature: A heat pumps is used for the entire energy volume (e.g., excess heat cooled from 25 °C to 15 °C, while the DH is heated from 35 °C to 75 °C).

Advantages:

- The temperature of the heat source is often warmer than a natural heat source thus enabling higher COP levels.
- Utilization of excess heat can simplify the operation for companies, including odour and noise from active cooling units as well as helping to reduce water consumption for wet coolers.
- Both the industry and the DH company can profit from the investment in the long run.
- For the industry, the utilisation of excess heat may represent a promotional value and/or a step towards CSR strategy goals.

Disadvantages:

- Companies usually require very short repayment periods (down to 1 year), while heat pumps for industrial excess heat often have a payback time of up to 5 years.
- It may be difficult to enter agreements with an industry which does not prioritise energy but rather focus on their production chain. Besides this, they will often not rely on the DH offtake of heat thus in any case install their own cooling units – at least as backup.
- If the industry closes, the DH company is left without this production capacity. In this case, the associated investment may be useless.

2.3 Geothermal heat

The temperature of the ground increases approximately 25-30 °C per km of depth. Geothermal heat is therefore attractive for district heating as its temperature may be higher than other natural heat sources.

Temperature:

Depending on the depth of the boreholes, different temperature levels can be achieved. In the Danish cases, temperatures of 43-48 °C are reached at 1.2-1.3 km of depth. In another case, the temperature is 73 °C at a depth of 2.6 km. Often the best properties for geothermal reservoirs are found at a depth between 800 and 3000 m. There are several reasons why drilling typically does not go deeper and aim for temperatures above 100 °C. A balance should be found between the achievable temperature levels and associated costs and risks. Both porosity and permeability decrease with the depth due to increased pressure, and the rising temperatures cause chemical precipitation processes that fill the pores in the sandstone. The properties of the underground are, however, varying heavily between the different global and even local regions. New geothermal systems are currently being planned for Danish DH based on heat purchase agreements in order to reduce the risks for the individual DH company.

Advantages:

- The heat source has a high temperature. How deep it is profitable to drill depends on the temperature gradient for the location in question.

Disadvantages:

- Risk of unsuccessful effort to reach the expected heat supply thus risking that the plans of a geothermal plant must be cancelled after significant spendings associated with the attempt.
- Risk of precipitation of iron and lime to be handled (increasing costs).

2.4 Sewage water

Sewage water (or “wastewater”) treatment plants are often located in places where it is possible to utilise the heat for district heating. However, in some cases the distance to the DH network is too long and the heat potential too small to ensure that the solution is feasible compared to alternative options.

Temperature:

The temperature in an outlet from a typical Danish sewage treatment plant is approximately 10 °C, and during the summer period up to about 20 °C.

Advantages:

- The heat can be extracted all – or almost all – year round, though it can provide more heat during the summer period than in winter due to the temperature of the water.
- A relatively easy installation process which does not require special environmental permits compared to groundwater heat pumps.

Disadvantages:

- The heat production is highly dependent on the continuous operation of the wastewater treatment plant. If it closes or changes handled volumes, the heat pump operation is directly affected.
- The sewage water will in general not be sufficient to cover the DH demand since there is simply less potential energy present in the wastewater produced per inhabitant than what the same person needs to cover the heating demand. Hence, sewage water is typically considered *part of* an energy (and heat source) mix rather than covering the majority of the DH demand.
- It must be ensured that no fouling or corrosion occurs, to avoid environmental contamination.

2.5 Groundwater/drinking water

Groundwater and drinking water are in general a sensitive topic and the concerns regarding risk of contamination often lead to a longer permitting process or even a halt in the initial phase. In many locations groundwater is suitable for the establishment of groundwater-based heat pumps. However, it is important to examine local conditions before investing in a heat pump. Groundwater is found in different depths and the groundwater reservoirs are of different sizes. For groundwater to be relevant as a heat source, it must be possible to pump up relatively large amounts of water from the groundwater. As a first step it can be investigated if nearby drillings can indicate the amount of groundwater. A test drilling can be a second step to ensure that there is sufficient flow for a desired heat pump capacity.

Another option is to cool drinking water, which is in any case pumped from the ground. However, the amounts may not be aligned with the heat demand and the supply will therefore only represent part of the heat supply similar to what is seen for sewage water.

Temperature:

The temperature of groundwater in Denmark is largely constant all year, with temperature approximately between 8-11°C.

Advantages:

- Numerous groundwater reservoirs suitable for the establishment of groundwater-based heat pumps.
- Data from existing boreholes may be available in national databases which can indicate whether or not there is a possibility to use groundwater as a heat source.
- The temperature of groundwater is approximately the same all year round thus representing a stable heat pump operation and heat supply.
- With regular maintenance, a groundwater-based heat pump solution can have a long service lifetime. In Denmark there are boreholes which are more than 100 years old.

Disadvantages:

- The feasibility studies to assess the technical possibility of groundwater heat pump operation can be expensive when it comes to pumping tests to check the actual conditions of the area.
- Due to the value of clean groundwater and the large amounts extracted, there is often a strong concern associated with the establishment of groundwater heat pump facilities and their potential impact on groundwater resources. Preliminary studies and environmental assessment from the municipality will often take at least one year before having the approval. In some cases, it might take even several years.
- It will most likely not be possible to obtain permission for groundwater heat pumps in areas with special drinking water interests due to the protection of future water supply.

2.6 Lake, river, or sea

For both seawater, lakes and rivers, there are temperature constraints. It must be ensured that the inlet water does not drop below approximately 4 °C for an extended period in winter since the risk of freezing in the heat pump must be avoided. In these systems, regular cleaning of heat exchangers must be taken into account. Some things may be filtered while others cannot. As an example, for sea water heat pumps, the formation of mussel larvae can be filtered whereas biofouling cannot. In some cases, it can be useful to install a back flush option. In any case it is important to ensure the ability to dismantle the heat exchanger and install valves to avoid the need of emptying of the pipes and remaining system when doing so.

Temperature:

Compared to the sea, lakes tend to develop a water stratification due to stagnation. As an example, the temperature of Danish lakes fluctuates significantly between summer and

winter, going from 4 °C up to 17-18 °C. In other countries the differences may be even higher.
Concerning rivers and streams, the temperature is usually relatively stable though it depends on the size, location, and source of the river (e.g., if glacier meltwater affects the temperature). When the stream is an effluent from a lake, then its temperature is highly dependent on the lake water.

Advantages:

- Many lakes and streams/rivers are big enough to allow extraction of heat through heat pumps.
- Extraction and discharge of lake or river water is relatively cheap and easy to establish compared to other solutions.

Disadvantages:

- Lakes, rivers/streams and the sea cool down during the autumn and winter and may freeze over, which correlates with the periods when most heat is required.
- The permitting process can be time consuming due to concerns regarding contamination.
- Heat exchangers and other components require regular cleaning due to fouling.
- The water intake is difficult to access (inspect, clean or repair) due to its position somewhat away from shore to ensure sufficient water flow.

2.7 Air

Air-source heat pumps represents the majority of heat pump systems currently installed in Danish DH as described in the document “Market status, incentives and policies in Denmark”.

Temperature:

The temperature of outdoor air follows the seasons which during a year follows an almost inverse trend compared to the heating demand but is highly dependent on the geographical location. Even small distances between locations may represent a change in climate conditions. This can a result of a difference between coastal and inland climate or a difference in height above sea level. Local conditions should be taken into account when evaluating the feasibility of an air-source heat pump.

Advantages:

- The benefits of using air as heat source include the abundancy of ambient air, i.e., the availability everywhere.

- Typically, the permission process is shorter and less comprehensive compared to other sources.

Disadvantages:

- Typically, the seasonal COP (SCOP) is lower than for other heat sources. The varying air temperature reduces the COP and thermal capacity when heat is needed the most in winter.
- The air coolers require more space than evaporators used for other heat sources. In this respect it is relevant to consider both the area allocated for the air vents and the necessary open space around them to ensure a free flow of air.
- Since the energy density of air is relatively low, a large flow is needed for a given heat supply, compared to other sources.
- Defrosting of the evaporators to handle condensed, frozen moisture from the air, represents a loss of energy.

More information on air as heat source is found in the dedicated document in this series: *”Air-source heat pump operation”*.

REFRIGERANTS

Technical Report of the IEA DHC TS3 "Hybrid Energy Networks", subtask A "Technologies and synergy potential", WP2 "Experiences with hybrid energy networks based on large-scale heat pumps": *Refrigerants*.

Author: Daniel Trier

PlanEnergi
Nørregade 13, 1st fl.
1165 Copenhagen K
Denmark

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Content

1 Historical development of refrigerants

1.1 Overview

A simplified historical development of refrigerant categories is illustrated in Figure 1. Though the use of the refrigerant categories overlaps, the timeline illustrates the development towards the ambition of reducing the impact of their ozone depletion potential (ODP) and global warming potential (GWP). The natural refrigerants have been present along the way, but only to a smaller extent used.

The Montreal Protocol and the associated Kigali Amendment[1] has ensured a vital shift away from the most harmful substances in terms of their ODP and GWP. However, much work is still to be done with regards to the agreements' implementation, and natural refrigerants could be a suitable further step.

CFCs[2] have a high ODP caused by the gases rising to the atmosphere where they – as a result of ultraviolet radiation – react to release the chlorine atom, which reacts with ozone thereby reducing the ozone layer. Besides this, the GWP is high. HCFCs[3] have an ODP and GWP lower than CFCs but the values are still substantial. HFCs[4] have been implemented as replacements since they have no ODP due to the fact that – unlike CFCs and HCFCs – HFCs have no chlorine content. To reduce also the GWP, HFOs[5] have been implemented representing low GWP values.

Figure 1. Historical development within refrigerant use.

1.2 Concerning HFOs

Though the HFOs may by some be considered refrigerants for the future, they too involve drawbacks. HFOs are broken down in the atmosphere within two weeks to create trifluoroacetic acid (TFA) in the large category of per- and polyfluoroalkyl substances, PFAS

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[1] See treaties.un.org/Pages/ViewDetails.aspx?src=IND&mtdsg_no=XXVII-2-f&chapter=27&clang=_en#1.

[2] Chlorofluorocarbons

[3] Hydrochlorofluorocarbons

[4] Hydrofluorocarbons

[5] Hydrofluoroolefins

(according to OECD's definition[6]) all containing carbon-fluorine bonds. As an example, R1234yf (with the chemical formula $C_3H_2F_4$) reacts and creates C_2F_4O which hydrolyses to TFA with the chemical formula $C_2HF_3O_2$. TFA accumulates in the environment since it is very stable.

Due to the concern related to the environmental and health effects of TFA, studies have been carried out to identify its presence. A study[7] funded by the German government investigated the presence of short chain and ultra-short-chain PFAS (with TFA being one of them). This study identified TFA in 47 samples, and in 2021 it was identified in 219 out of 247 (89%) of investigated groundwater boreholes in a Danish study[8].

A proposal regarding the restriction of PFAS substances including some HFC and HFO refrigerants have been submitted to the European Chemicals Agency (ECHA) by the five countries Germany, the Netherlands, Sweden, Norway, and Denmark[9].

The similarity to the effect seen for CFCs, where the chemical breakdown in the atmosphere results in undesired side-effects, are remarkable. Lack of awareness when the ambition to handle one problem ends up causing another cannot be an excuse not to act accordingly to mitigate the side-effect.

Since positive outcomes using natural refrigerants have been proven in many cases, their use can be applied as a prerequisite already in the tender documents as it is often done in Danish cases. From the knowledge available it can only be recommended to ensure the use of natural refrigerants in the expected deployment of large-scale heat pumps for district heating. This can be applied even without stating which type of heat pump (or type of natural refrigerant) to be used in a functional tender. More information on tendering process can be found in the document "Tendering process".

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[6] OECDs definition: *"PFAS's are defined as fluorinated substances that contain at least one fully fluorinated methyl or methylene carbon atom (without any H/Cl/Br/I atom attached to it), i.e. with a few noted exceptions, any chemical with at least a perfluorinated methyl group (–CF3) or a perfluorinated methylene group (–CF2–) is a PFAS."* Environment Directorate Chemicals and Biotechnology Committee, Series on Risk Management No.61, "Reconciling Terminology of the Universe of Per- and Polyfluoroalkyl Substances: Recommendations and Practical Guidance".

[7] "Ultra-Short-Chain PFASs in the Sources of German Drinking Water: Prevalent, Overlooked, Difficult to Remove, and Unregulated", May 4th 2022, Environmental Science & Technology, doi.org/10.1021/acs.est.1c07949.

[8] mst.dk/media/211541/fagligt-notat-om-resultater-af-massescreening-2020.pdf

[9] echa.europa.eu/da/-/echa-publishes-pfas-restriction-proposal

2 Natural refrigerants

2.1 Overview of commonly used natural refrigerants

The most typical natural refrigerants for large-scale DH heat pumps are:

- ammonia (NH_3) with the refrigerant number R717 (GWP: 0, ODP: 0)
- carbon dioxide[10] (CO_2) with the refrigerant number R744 (GWP: 1, ODP: 0)
- propane (C_3H_8) with the refrigerant number R290 (GWP: 3, ODP: 0)
- isobutane (C_4H_8) with the refrigerant number R600a (GWP: 3, ODP: 0)

Natural refrigerants are widely used in heat pumps for DH in Denmark. Most of the heat pump installations use ammonia as refrigerant though the market for CO_2 solutions is increasing. In the cases evaluated in "Market status, incentives and policies in Denmark", where data on refrigerants are gathered, more than two out of three systems use ammonia as refrigerant. Typically, CO_2 is found in smaller heat pumps (or in case more individual units are combined), whereas larger systems often use ammonia.

No single heat pump technology covers all applications and the best solution will depend on the given case. As an example, for CO_2 heat pumps, the COP is less sensitive to the required outlet temperature on the condenser side (i.e., the DH forward temperature) compared to ammonia heat pumps (but is in turn more sensitive to high inlet temperatures on the condenser side). Typically a transcritical CO_2 cycle is suited for systems where there is a small temperature difference of the heat source, while the heat sink (i.e., DH network) has a large difference between return and forward temperature. In general, high COP levels are key, but other factors such as flexibility, costs and control options are also important when it comes to evaluating the feasibility and choosing a solution.

2.2 Advantages and disadvantages

A list of key advantages and disadvantages of natural refrigerants is seen below.

- No ODP
- Low or no GWP.
- No TFA output to the environment
- CO_2 is operating under high pressure due to its properties
- Ammonia is toxic in case of leakages causing high concentrations
- The hydrocarbons propane and isobutane are flammable

The abovementioned disadvantages require precautionary measures but in turn, they will not leave a negative environmental impact behind as a result of the chosen refrigerant.

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[10] Since the molecular formula CO_2 is often used instead of "carbon dioxide", this term is also used.

AIR-SOURCE HEAT PUMP OPERATION

Technical Report of the IEA DHC TS3 “Hybrid Energy Networks”, subtask A “Technologies and synergy potential”, WP2 “Experiences with hybrid energy networks based on large-scale heat pumps”: *Air-source heat pump operation*.

Authors: Daniel Trier
and Matteo Daminato

PlanEnergi
Nørregade 13, 1st fl.
1165 Copenhagen K
Denmark

10-02-2023

Content

1 General experiences

1.1 Operation throughout the year

Something to consider for all type of heat sources is how they perform and handle non-ideal conditions. The expected daily and seasonal variations should be taken into account in the business case i.e., how the system is affected by real-life operation in the given case. Besides this, it is important to consider challenges affecting the performance and stability of the operation. In the following, selected key challenges are explained.

In general, examples from the significant number of air-source heat pumps installed in the past few years in Denmark show that the heat pumps are able to operate throughout the winter months. They are typically designed to expect downtime during the worst-case winter conditions simply due to the heat pumps being optimized to operate within a certain ambient air temperature span. The range could in principle be enlarged when designing the heat pump solution, but it would affect the performance for the worse during the remaining period of the year. To enable operation only for a rare case situation of extremely low outdoor temperatures (e.g., less than 1% of the time) is simply not feasible in a total system perspective, when the "cost" in terms of decreased performance and/or COP is taken into account. However, the DH company needs to take this into account and be prepared for such a situation with alternative capacity to ensure sufficient heat supply at all times.

1.2 Realtime monitoring of heat pump operation

The website www.heatpumpdata.eu does not only list and illustrate large-scale heat pumps for district heating in Denmark but also represents a data hub of monitoring the operation and performance of several of these. For the heat pumps connected with a data feed, the performance can be seen in real-time, illustrated in charts or downloaded for further processing. The data include thermal output, electricity demand, COP, temperature levels etc. To show only the systems with such a data connection, a filter option is applied in the top of the map as seen in Figure 1. Icons show the main heat source of the heat pump and a small lightning icon indicates a data connection.

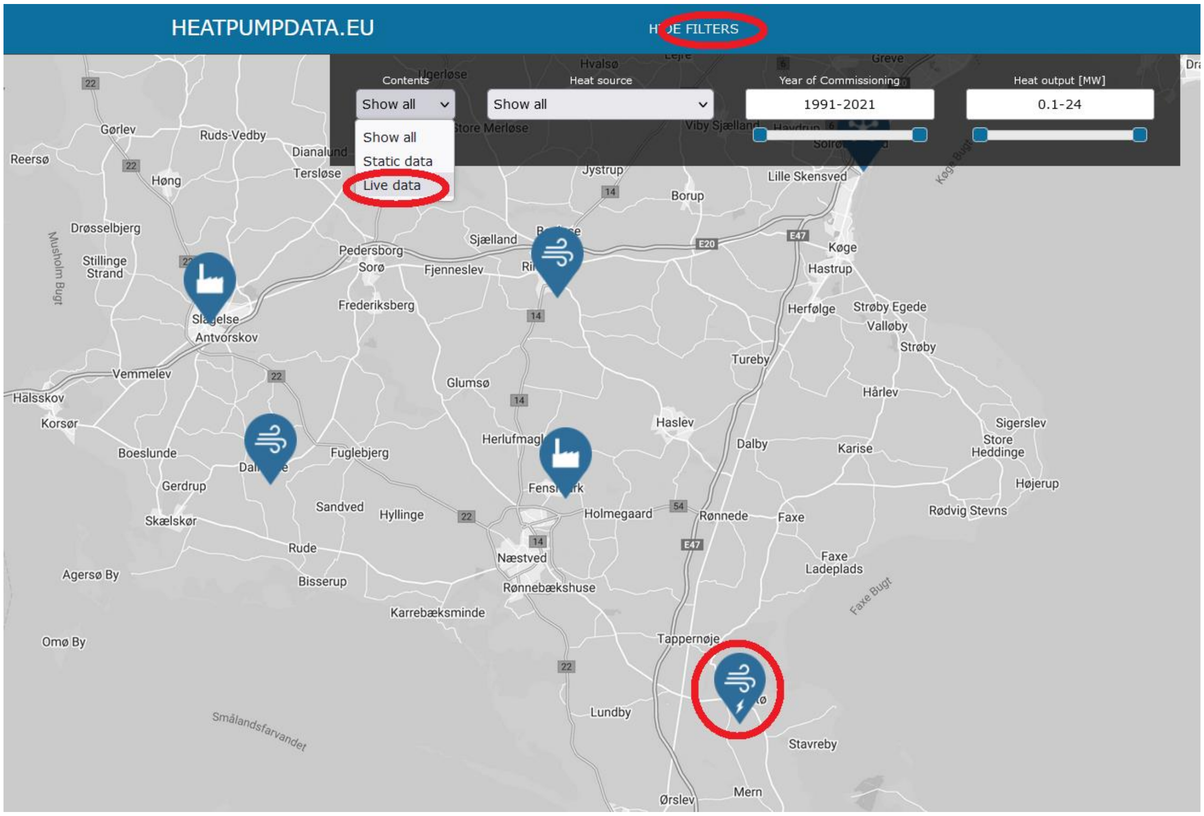

Figure 1. Section of heatpumpdata.eu website with indication how to filter for data connection (indicated with a small lightning in the bottom of the heat pump icon).

1.3 Condensate

The amount of condensed moisture can be substantial and it should be considered already in the planning phase how this is dealt with. In some cases, the water is simply absorbed by the ground below the evaporator unit (presuming the ground is prepared to handle it) whereas in other cases the water is led to a nearby sewer or even utilised for watering.

2 Defrosting

2.1 The need for defrosting

Air moisture condenses when the air is cooled by the evaporator unit. When the air temperature approaches 0 °C, this water will freeze on the evaporator unit. It should be noted that due to the cooling of the air, this happens already at ambient temperature *above* 0 °C.

To handle the build-up of ice on the evaporator unit, it is necessary to consider defrosting in the planning phase, control strategy and feasibility studies. Since the energy required for defrosting is not insignificant, this should be taken into account when evaluating the feasibility of different solutions.

2.2 The build-up of ice

Air source heat pumps operate with a temperature difference between the air and the refrigerant flowing inside the pipes, and the ΔT between these is usually 5-8 °C. Ambient air passing through the evaporator gets in contact with fins and pipes. These components are colder than the air. If the temperature is below the dewpoint of the air, then the humidity condenses on the evaporator. Drops start to accumulate on the surface, getting the evaporator wet.

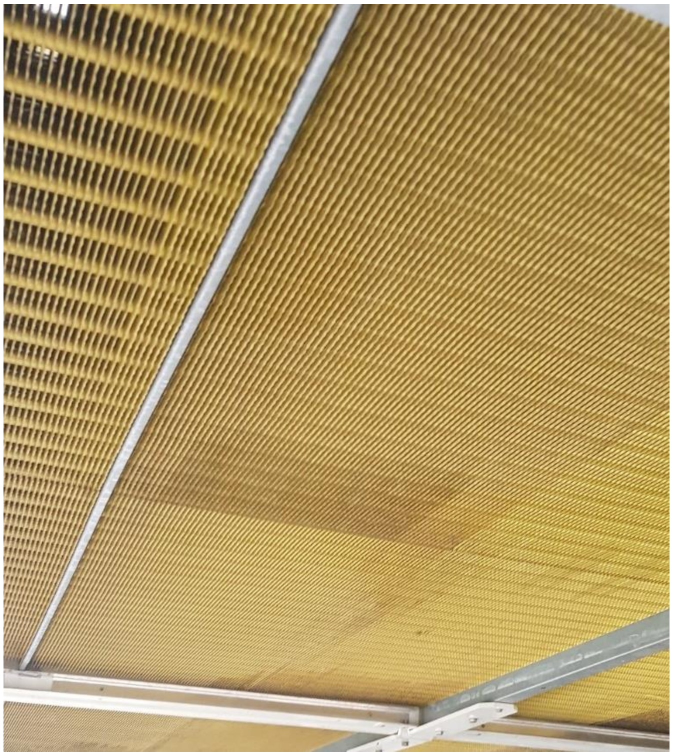

Figure 2. Flatbed evaporator fins seen from below.

Water deposition is beneficial for the operation of the heat pump since latent heat of condensation is released and used by the evaporator. The heat is then transferred to the refrigerant, and it is used for the operation. It accounts for approximately 25% of the total heat transferred in the evaporator.

When the ambient temperature drops below around 7 °C, the refrigerant temperature within the evaporator drops accordingly, reaching 0 °C and below. The water drops on the surface start to freeze, and a layer of ice grows. At first, the ice formation is beneficial in the same way of the water condensation: latent heat of solidification is released and transferred to the refrigerant.

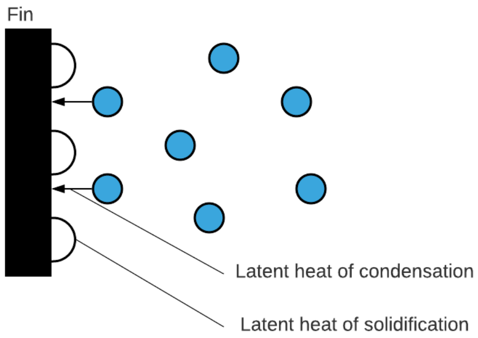

Figure 3. Condensation and solidification of air humidity.

The challenges start when the evaporation temperature stays below 0 °C for a longer period of time. The frost layer becomes thicker and thicker, and it starts to behave as a thermal resistance. The heat transfer coefficient between the air and the pipes reduces, and the amount of heat transferred to the refrigerant reduces as well. At the same time, as frost grows, the space between the fins reduces. Usually, the fin spacing is 3-7 mm to optimize the heat transfer surface and the compactness of the component. With increased frost thickness, the pressure drop throughout the component increases. At this point, the following two options are available:

Fixed fan speed

The fans are running at the same speed, regardless of the frost formation. In this case, since the pressure drop increases with increased ice thickness, the amount of air passing throughout the evaporator reduces, thus reducing the amount of heat transferred to the refrigerant.

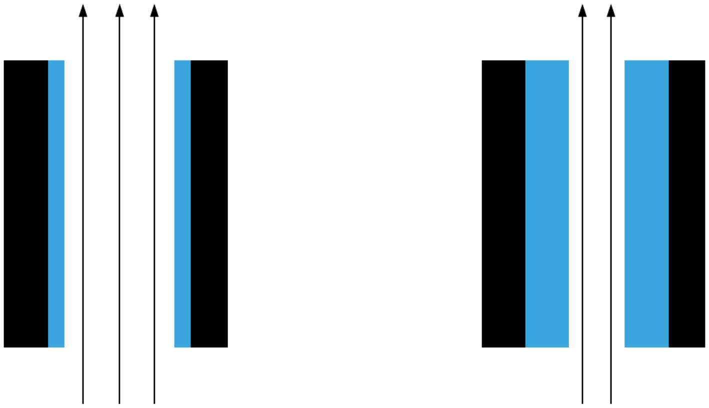

Figure 4. Fixed fan speed strategy.

Variable fan speed

Using a control system, a variable fan speed strategy can be set up in such a way that the fans increase their speed depending on the pressure drop to keep the heat load constant. This strategy ensures the normal operation of the components, but at the same time requires higher electricity consumption at the fans. The power consumption increases with an exponential trend, and it becomes very high when the fin spacing gets almost completely filled with ice. There might also be noise limitation for the maximum speed allowed.

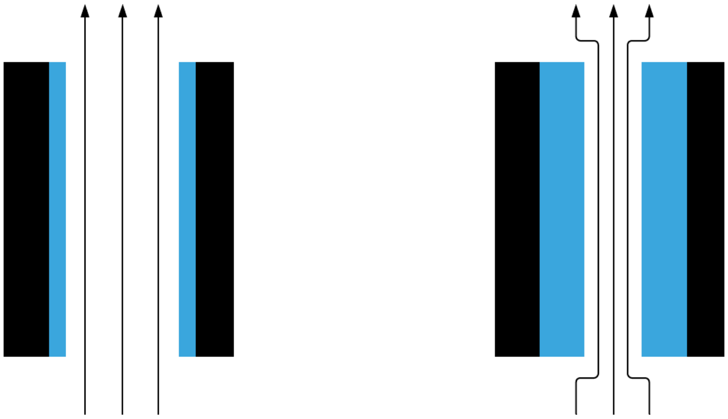

Figure 5. Variable fan speed strategy.

In both of these strategies, when the ice layer fills up completely the space between the fins, then the evaporators will stop working and no heat will be transferred to the refrigerant. Defrost is necessary to establish the correct functioning of the system before this happens.

2.3 Defrost strategies

Different defrost strategies are available to counteract the frost formation on the evaporator. They can be classified into different categories:

Upstream air treatment

This type of intervention aims to treat the air at the inlet of the evaporator to reduce the frost formation. Possible options are air humidity reduction at the fan inlet or preheating the air before it gets into the component. These interventions could have a beneficial effect on the operation since it would remove the frost issue, but on the other hand, it would increase the energy consumption and the initial investment since the components necessary to remove humidity or to heat up the air will be expensive and energy consuming.

Heat exchanger modification

The evaporator can be designed to get to the optimal configuration where frost formation is reduced at the minimum level and the heat pump operation optimized. The focus could be on:

- Increased fin spacing, to allow the maximum space between fins and extending the component operation by still keeping the component as compact as possible.
- Optimizing the tube geometry
- Selecting the right fin-type
- Coating of the fin since a cross-linked hydrophilic polymer coating can reduce the frost growth rate on a cold surface

None of these options prevent frost formation entirely. Every intervention should be balanced with economic considerations since the extra investment cost to include these modification does not necessarily lead to overall economic savings.

Defrost by cycle interruption

This category includes the most utilized and efficient techniques to perform evaporator defrost. To be able to remove the ice from the surface, the evaporator should be turned off. In this context, the large scale of the plant allows partial defrosting of the system since it is made of multiple evaporator sections running in parallel. One section at a time can be taken out of operation, defrosted, and then restarted. In this way, the system will always have enough evaporating capacity and keep a continuous heat production.

Different techniques are available such as:

- *Shutdown defrosting*, where the evaporator performing defrosting is shut down with the fans still blowing air on the surface. If the air is above the freezing point, the ice will melt.
- *Electric heating*, where electric devices are installed adjacent to the coil. Once frost is detected on the surface, the evaporator section is shut down and the heating elements are turned on with the fans still running. In this way the ice on the coil is melted by means of radiation, conduction, and convection.
- *Hot gas bypass*, where hot gases coming from the evaporators are bypassed into the evaporator section performing the defrost. Latent heat from the condensation of the superheated gas is released to melt the ice. This is a fast and the most common way to perform defrosting for commercial air-source heat pumps.

Regardless of the technique, the main goal is to optimize the operation. Depending on the location, on the number of evaporator sections installed, and on the size of the system, the defrost strategy should aim to minimise energy consumption. The analysis should focus on the maximum frost thickness allowed on the evaporator before defrosting is started, and on the defrost duration period.

2.4 Extraordinary occasions

What has been seen in specific winter conditions is that for downward air flow, a heavy snowfall at ambient air temperatures above 0 °C followed by sub-zero degrees may block the evaporators and freeze them over without the option of activating the normal defrosting. For upward air flow, the continuous operation blowing snow away from the fans may help to avoid this situation.

Under certain weather conditions it has been shown that the formation of an ice layer on the fans and inside the fan casing is creating a physical resistance for the rotating fans. Only a few cases of the occurrence have been gathered and research is ongoing as to how it is best avoided. One option is to include additional predefined circumstances where defrosting is activated in the heat pump control strategy. In case of supercooled moisture/water droplets, as seen in the rare occasion of freezing rain, ice is formed at the cold surface the droplets hit. When this surface is the protective grill/fan, it makes it difficult to defrost with a downward air flow. Further information on this is found in section 3.2.

3 Air flow

3.1 Type of air coolers

As a rough estimation, flatbed air coolers require approximately 100 m^2 of ground per MW of heat capacity. The air flow can be upwards or downwards.

Figure 6. Example of flatbed evaporators at Præstø Fjernvarme.

Another option is the V-shape evaporators as seen in Figure 7. With these, the air flow is always upwards. In some cases, it is more challenging to ensure sufficiently free flow of air around the evaporators compared to a flatbed solution.

Figure 7. Example of V-shape evaporators at Slagslunde Fjernvarme.

3.2 Direction of air flow

Advantages and disadvantages for both upwards and downward air direction are described in the following.

Downwards air direction

As shown in Figure 8, ambient air enters the evaporator from above and cools down, releasing heat to the refrigerant which evaporates. Cold air is denser compared to warm air, therefore the natural convection cooperates with the direction given by the fans. The air moves downwards. Once the cold air exits the evaporator, it stays on the ground level as it is denser than the surrounding air. In this way, the issues of mixing with warm air and short-circuits are averted.

For flatbed applications, the fans are installed on top of the coil. During their operation, the fans waste a considerable amount of energy (50% of their total use) as heat due to mechanical friction. With the downwards flow direction, the heat released from the fans is utilized within the evaporator component and it increases the capacity of the evaporator. However, this has a marginal impact, as it only increases the COP slightly.

Another positive impact of having downwards air flow is linked with the water condensation on the evaporator surface. When water condenses on pipes and fins, the fans blowing downwards will cooperate with gravity on getting rid of the water. The accumulation of water will be reduced during the operation and it will also reduce the amount of frost building up on the evaporator surface.

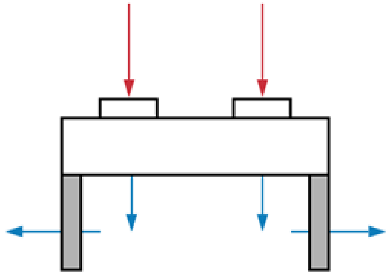

Figure 8. Downwards air direction of a flatbed evaporator.

Upwards air direction

As shown in Figure 9 ambient air enters the evaporator from below and cools down moving upwards. When cold air exits the evaporator, it may fall down due to increased density. This imposes a risk for short-circuits by recirculation of cooled air to the evaporator. The effect is reduced by the occurrence of wind blowing the cooled air away.

Hence, the risk, level and impact of recirculation are not fixed parameters, but varies along with the wind speed and direction.

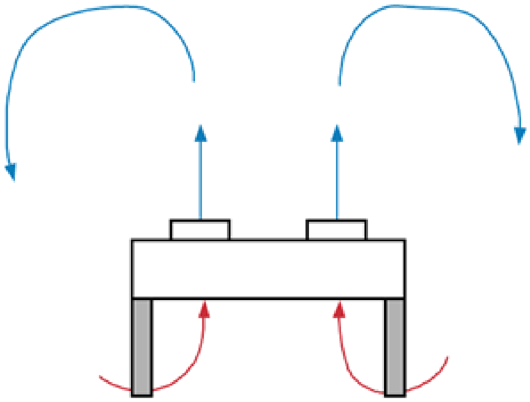

Figure 9. Upwards air direction of a flatbed evaporator.

With the installation of a diffuser at the outlet of the fans, cold air will be thrown further away, preventing recirculation and short-circuit.
On the other hand, the advantage of having upwards air direction is that instead of being pushed in, the air is sucked through the cooling surface, ensuring the best possible flow distribution and the best possible utilization of the cooling surface.

With an upwards air direction, the noise production is slightly reduced. The safety grill on top of the fans (see Figure 10) is placed at the outlet of the fan, ensuring higher efficiency and less noise.

Figure 10. Close-up of the protective safety-grill on top of the fans of a flatbed evaporator.

Regarding the distribution of cold air, with upwards direction improved mixing with uncooled air reduces potential inconvenience caused by the cold air. In contrast, with a downwards air flow direction, the air could lie as a duvet over the nearby area.

An important factor that should be considered is the temperature below the evaporators and the ice formation on the ground. During the operation, water condensation and defrost will occur and the water from the evaporators will fall to the ground. If the air temperature is below the freezing point of water, a layer of ice will grow below the evaporators until the temperature rises again to a sufficient level to melt the ice. For this reason, it is important to keep in mind to place the evaporators high enough to allow a gap between the evaporator components and the ground while ensuring sufficiently free flow of air.

3.3 Recirculation of air

In some cases, walls surrounding the evaporators are installed to mitigate an issue of recirculating air as seen in Figure 11. However, in the most common solution is for flatbed evaporators to be installed without such wall mount.

Figure 11. Evaporators with wall mount to reduce air recirculation at Karup Fjernvarme. (Credit: Morten Pedersen. https://viborg-folkeblad.dk/rundtomviborg/trods-gasprisernes-himmelflugt-lokalt-varmevaerk-styrer-flot-uden-om-prisstigninger#slide0)

LARGE-SCALE HEAT PUMPS IN DISTRICT HEATING NETWORKS

TENDERING PROCESS

IEA DHC ANNEX TS3 – HYBRID ENERGY NETWORKS

Technical Report of the IEA DHC TS3 “Hybrid Energy Networks”, subtask A “Technologies and synergy potential”, WP2 “Experiences with hybrid energy networks based on large-scale heat pumps”: *Tendering process*.

Author: Daniel Trier

PlanEnergi
Nørregade 13, 1st fl.
1165 Copenhagen K
Denmark

10-02-2023

Content

1 The process

The stepwise process of establishing a large scale heat pump for district heating is illustrated in Figure 1, representing the timeline from initial feasibility study through permissions from authorities, purchase of the land, tendering, construction, commissioning and follow-up to check if there are issues to be covered by the guarantee. In this document the focus is on the tendering phase. Though the different steps are general, the approach chosen in practice will vary from what is described in the following.

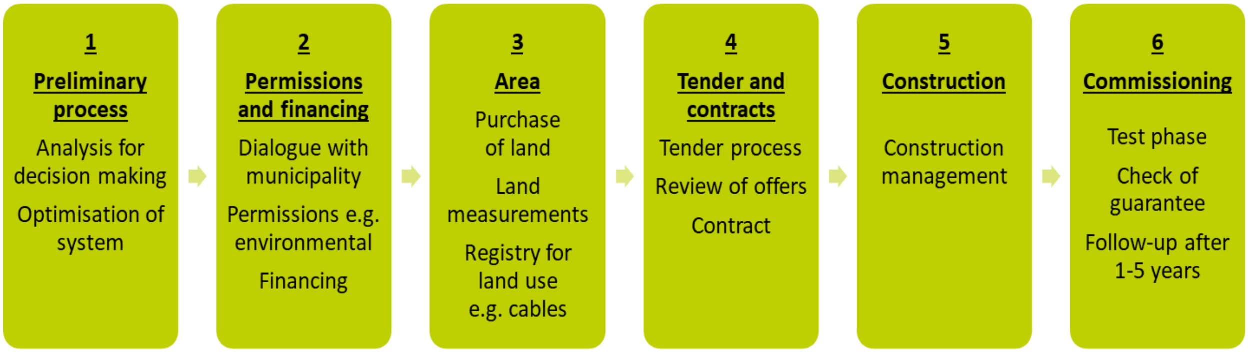

Figure 1. Stages of the process of establishing a heat pump.

2 Tender format

One approach is to have a functional tender to gather several different options to fulfil a given task (e.g. to cover approx. 70% of the annual heat demand of the district heating plant in question). Contractors are continuously working to optimize their proposed solutions by adjusting number and type of compressors, evaporators etc. in bespoke configurations. Hence, a preconfigured design may rule out the alternative, better and more feasible options that contractors otherwise could propose based on their latest experiences and knowledge.

The format reduces the time and efforts spent on preparing the tender documents since the detailed dimensioning etc. is made afterwards. However, the district heating company or its consultant identifies the preconditions such as heat source, location and connection to the district heating plant/network etc. and prepares the initial pre-design. The exact border between what must be included in the offer and what remains the responsibility of the district heating company must be clearly defined. This applies both to physical borders (identifiable on P&I diagram) and non-physical interfaces. One example is who is responsible to fulfil the criteria of the electricity grid DSO. For more information on this topic, see the document “Economics and the electricity grid connection”.

Even without detailed dimensioning already prepared in the tendering documents, the process requires in-depth technical knowledge to be able to evaluate the various proposals and compare the value of each of them.

As described in the document ”Configurations and energy system integration”, it may be relevant to compare different solutions to identify the benefit of either an efficient, yet expensive system against a cheaper but less efficient option.

In the evaluation process it is possible to include an intermediate meeting to discuss the proposed solutions with each of the tenderers. This way questions and/or identified issues conflicting with the predefined terms in the tender can be highlighted to enable an updated version of each offer where all conditions are met.

3 Contractor

A turnkey contractor holds the responsibility of coordinating the different tasks including any delays caused by the interaction between subcontractors. It is also easier this way to place the responsibility in case the system does not perform as it should. However, the single tasks of the project may require know-how which a total contractor cannot cover alone. Hence, skilled subcontractors are required as part of a consortium. A turnkey contractor may include an overhead in their price to cover organizing and risks involved with signing the subcontractor. Besides this, the single point of entry (turnkey contractor) results in less dialogue between the subcontractors handling the construction, and the district heating company, thus potentially hindering efficient communication where optimization of smaller practical issues potentially could be identified and handled on site.

4 Comparing offers

While the bespoke configurations can result in optimized efficiency, they make it more complex to predict final performance figures. The feasibility comparison should take into account costs for operation and maintenance, investment costs, displaced fuel costs, etc. and evaluate based on net present value to identify the best solution for the district heating company. This requires an evaluation, which calculates the operation of the system with the proposed solution. One option is to include a template how the calculation will be made as an annex to the tender documents so that the contractors tenderers may investigate the effect of different solutions they could offer.

The tender may be made flexible in terms of the exact heating capacity, since a proposed configuration could enable significant financial benefits by deviating slightly from the initially expected capacity due to the combination and number of compressor units, evaporators etc. In other words, the tenderer may for example have identified the option of installing extra capacity with little extra investment to match a suitable combination of compressor units and evaporator units for the given case. With this approach the variety of potential components and units increases. In turn, the period for running-in and commissioning is more time consuming than a tender with a predefined detailed design.

Also non-economical factors are part of the evaluation criteria (though the feasibility are weighted highest). General quality of the components and the configuration, the contractors' experience, references and team, and the offered service option can be part of the evaluation.

5 Performance check

After the commissioning but before the official hand over of the heat pump, a test phase must be carried out to prove the reliability of the system as well as a check of the performance and efficiency.

In the tender documents it is possible to include the option of both penalty and bonus if the final system turns out to perform worse or better than initially promised. However, an uncertainty range without penalty or bonus may be relevant to take measurement uncertainties into account. The calculation method should be clearly described already in the tender documents to reduce the risk of disagreements on a financial penalty (subtraction from the final payment share).
In this respect it is important to define the preconditions for the evaluation data i.e. which period(s) and who decides this, length of the measuring periods, how much data (handpicked periods or all applicable data included) and which sensors are used.

What has been seen from several realised projects is that some systems are performing worse than expected while others perform better. Hence, experiences show that both penalties and bonuses can come into play. A penalty for lack of performance (power and efficiency) may not represent the actual cost for the district heating company with no upper limit, since the tenderers may not be willing to accept a potential fine corresponding to the actual value that may be substantial. Hence, the district heating company may have to accept a certain risk to obtain the desired (amount of) offer(s). Similarly, a bonus should have an upper limit since the district heating company will not benefit proportionally from an unlimited amount of extra capacity.

6 Waste heat agreement between industry and DH

When waste heat is to be utilized, a formal agreement is to be made between the industry providing the heat and the district heating company. This should include the following points[1]:

- General terms
    - Involved partners etc.
    - Purpose of the agreement
    - Who will handle legally required reporting
- Establishing and ownership
    - Who owns, establishes and operates which parts of the setup (heat exchanger, pipes, pumps, compressors etc.)
    - Ownership and obligation borders
- Supply and off-take obligations
    - Amounts by supplier and periods
    - Off-take amounts and periods
    - Properties of the supplied heat
    - In case of downtime
- Operation and maintenance
    - Operation and maintenance obligations by each part
    - Mutual duty to notify each other
    - Allowed out-time due to maintenance
- Measurements
    - Measuring units to be used for the cost calculation
    - Ownership and responsibility of measuring units
- Prices
    - Prices
    - Terms of payment
- Agreement breaches
    - Definition of breach of the agreement
    - Liability
    - Force majeure
- Timeline

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[1] Based on list from Danish District Heating Association ”Aftalepunkter ved indgåelse af aftale om køb af overskudsvarme” (Agreement on the purchase on waste heat). www.danskfjernvarme.dk/-/media/danskfjernvarme/gronenergi/projekter/drejebog-om-store-varmepumper/drejebog_2017_ny/aftalepunkter-ved-indg%C3%A5else-af-aftale-om-k%C3%B8b-af-overskudsvarme_januar_2015.pdf.

  - Date of the agreement entering into force
  - Start date of the heating supply
  - Duration of the agreement
  - Termination of the agreement
- Renegotiation
- How to handle disputes

LARGE-SCALE HEAT PUMPS IN DISTRICT HEATING NETWORKS

ECONOMICS AND THE ELECTRICITY GRID CONNECTION

IEA DHC ANNEX TS3 – HYBRID ENERGY NETWORKS

Technical Report of the IEA DHC TS3 “Hybrid Energy Networks”, subtask A “Technologies and synergy potential”, WP2 “Experiences with hybrid energy networks based on large-scale heat pumps”: *Economics and the electricity grid connection*.

Author: Daniel Trier

PlanEnergi
Nørregade 13, 1st fl.
1165 Copenhagen K
Denmark

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Content

1 Economics of heat pumps

1.1 Electricity prices

The electricity prices have seen large variations during the last couple of years compared to previous periods, as illustrated in the Figure 1 example for eastern Denmark. The trend of increasing prices has shown not to continue in 2023 and as indicated by IEA the levels are expected to be lower compared to 2022 in the coming years[1]. Besides this, the average values also cover fluctuations including hours with low prices. Two similar average values can hide big differences in terms of the hourly values behind it. Hence, high-resolution (hourly) analyses are relevant when calculating the operation costs of a heat pump.

Heat pumps for district heating will typically prioritize operation according to not lowest electricity prices – or at least avoid the most expensive prices. Hence, the average spot price will not necessarily be representative since an average operation electricity price can be below the market average. However, the weighted average during operation will also be affected by the load curve representing a larger electricity demand in winter than in summer due to the space heat demand. This means that for a heat pump with surplus capacity in summer and insufficient capacity in winter, the weighted average will be affected by the affected more by winter electricity prices than the corresponding summer values.

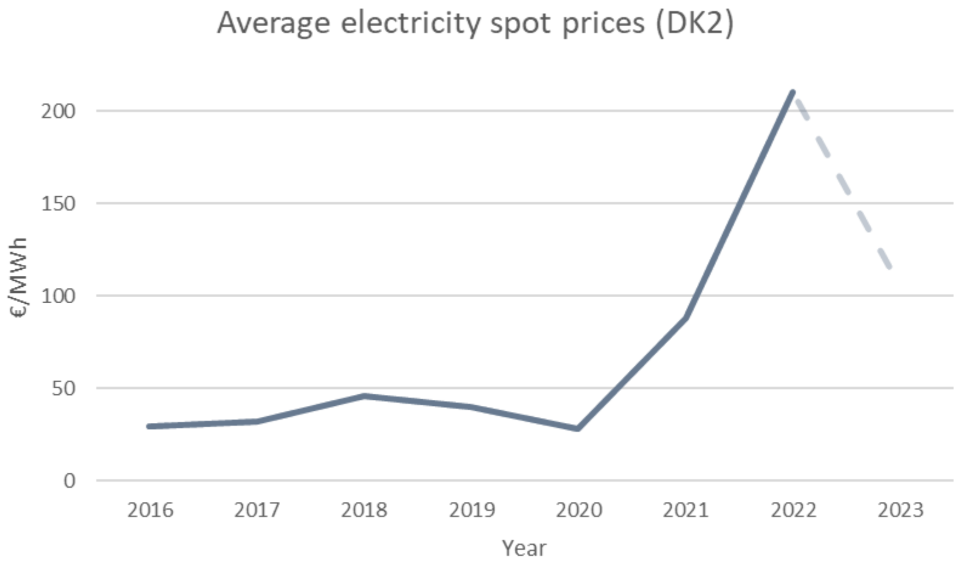

Figure 1. Average electricity spot prices for eastern Denmark 2016-2022 incl. indication of the average level at the of beginning of 2023.

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[1] IEA, *Electricity Market Report 2023*, Indexed quarterly average wholesale prices for selected regions, 2019-2024, www.iea.org/reports/electricity-market-report-2023.

1.2 Investment costs categories

The capital costs cover a range of different sub-categories with the main hardware units representing half or even more of the total capital costs (compressor units being the larger of the two):

- Main hardware
    - Compressor units
    - Evaporators and cooling circuit
- Secondary hardware
    - DH connection (e.g., transmission line depending on location)
    - Pumps and electric motors
    - Valves
    - Technical building/room
    - Noise and vibration reduction (if required)
    - Heat exchangers
    - Refrigerant, oil and other liquids
- Labour
    - Design, documentation and quality assurance
    - Site conditions check (area measurements, condensate drainage ability)
    - Consultants and gathering permissions from authorities
    - Installation of heat pump unit and associated equipment
    - Piping
    - Insulation of the heat pump and piping
    - Electrical installation
- Other
    - Control system of heat pump
    - Integration in the DH control system (SCADA)
    - Electricity supply (connection fee and remote surveillance/control hardware)

1.3 Operation costs

Operation & maintenance (O&M) – not including the cost of electricity and associated taxes/tariffs – represent service agreement fee and spare parts/replacements not covered by such agreement as well as the labour costs associated with the operation.

The compressor unit(s) are the most critical component. There is a distinction between piston and screw compressors, where piston compressors require more maintenance due to a larger number and complexity of moving parts. As a general estimation, inspections seen in the table below are expected.

All types of systems	
Every 5000 hours	Small inspection with control of oil , filters, safety automation etc.
Every year	Statutory inspection of pressure vessels, safety valves, piping systems, gas detection system, etc.
Every 4th and 8th year	Thorough inspection of pressure vessels and piping system
Screw compressors	
Every 30-40000 hours	Inspection and possibly replacements
Piston compressors	
Every 10000 hours	Surveying and checking, possible replacements
Every 30000 hours	Main inspection, replacements of bearing and maintenance rod bolts

1.4 Average total heat price

An example of heat price distribution between the main cost categories (capital costs, operation & maintenance, and electricity) is seen below in Figure 2. Average electricity costs including taxes/tariffs are assumed to be either 80, 120 or 160 €/MWh to indicate examples of lower, medium or higher levels respectively though neither of these represents extreme values. O&M represents around 3 €/MWh. The capital costs are based on a summary of real cases applying an interest rate of 3.5% and a payment period of 15 years. This results in heat production costs between 39 and 63 €/MWh.

Since most of the examples gathered lies a few years in the past and prices have been seen to increase significantly in 2022 compared to previous years, the similar figure has been applied adding 30% to the capital costs as an approximation to indicate the cost difference between the average realised costs and what is expected in 2023. This results in Figure 3. In this case, the average heat production prices ranges between 43 and 67 €/MWh.

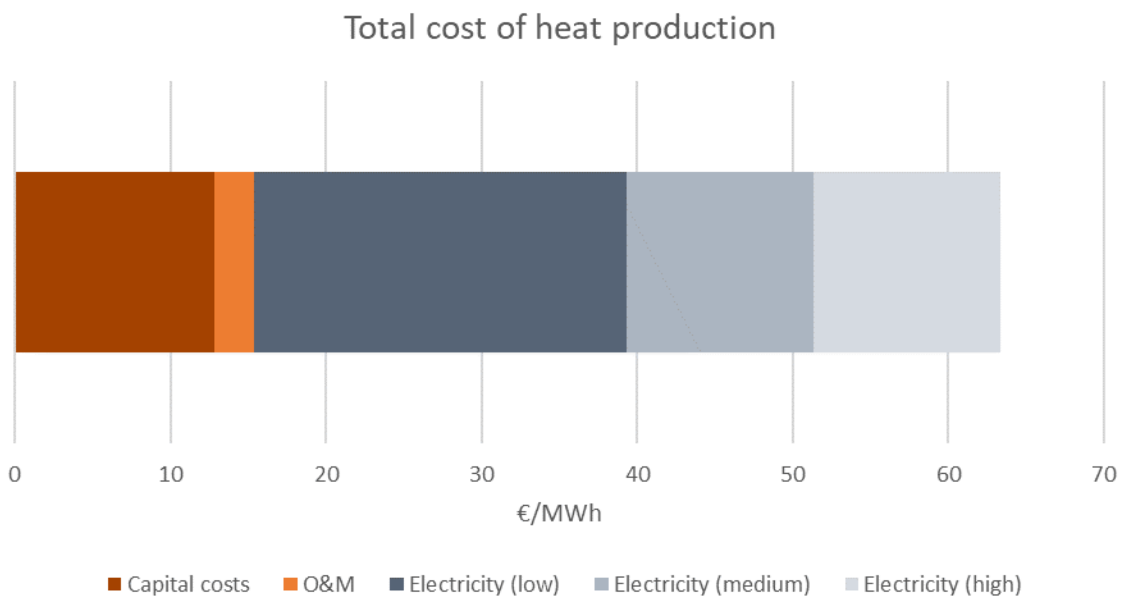

Figure 2. Total cost of heat production based on real cases.

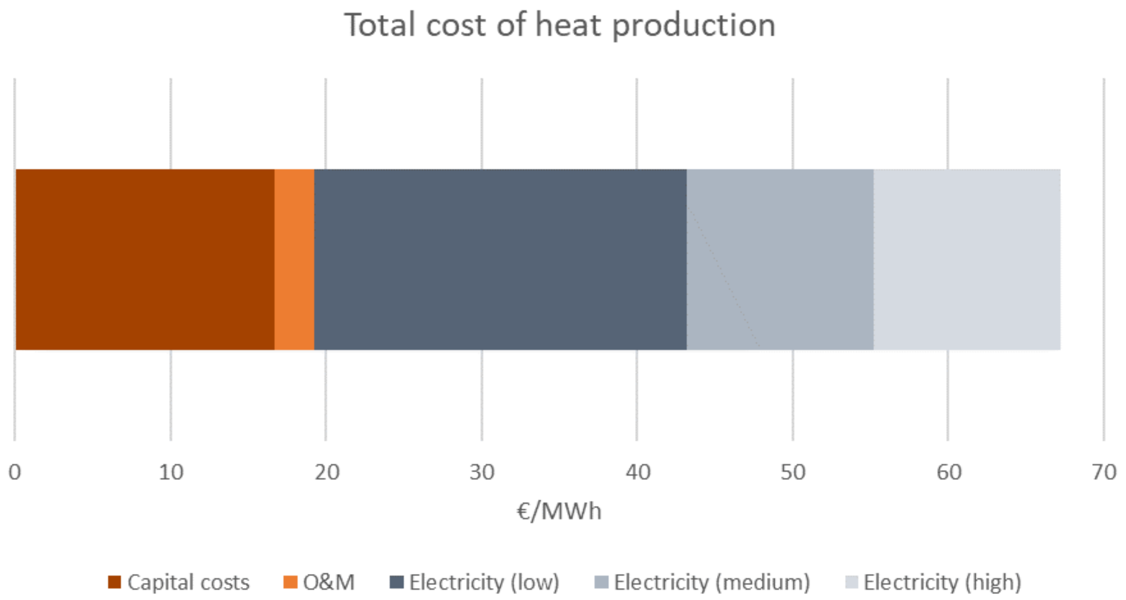

Figure 3. Total cost of heat production based on updated heat pump investment cost levels.

Another way to illustrate cost distribution is seen in Figure 4 where the the split between the main cost categories are seen for the case of a low, medium and high electricity price respectively.

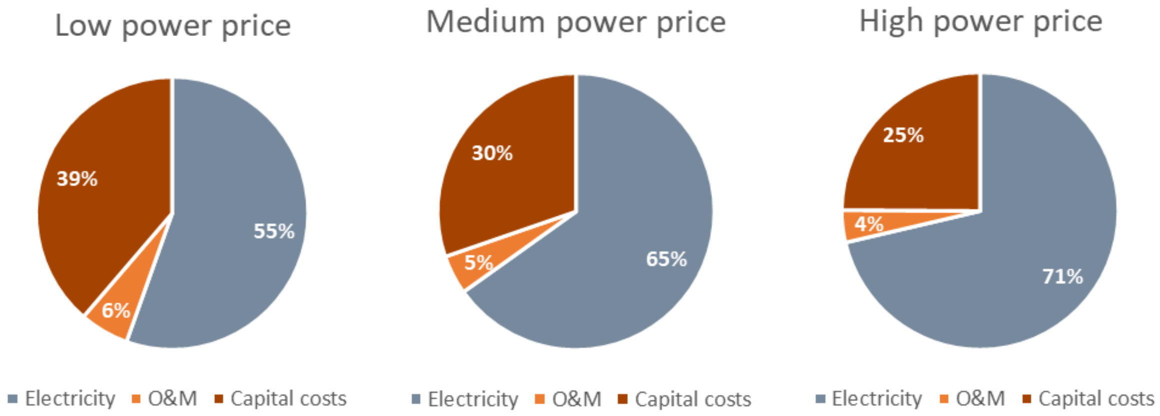

Figure 4. Cost distribution examples based updated heat pump investment cost levels.

Regarding the comparison between different configurations and the optimization of design considering both efficiency and costs, see also the document “Configurations and energy system integration”.

2 Electricity grid connection

2.1 Connection points

It is recommended to initiate a dialogue with the DSO early in the process to evaluate what options are present for the point of connection (POC). The grid tariffs may be very dependent on the POC and voltage level where the principle is to pay a fee for the category of grid used. Hence, if the low-voltage grid is not used, due to a POC at a higher voltage level, the low-voltage grid fee does not apply.

Relevant voltage level options for heat pumps in a Danish context:

- A-High: The costumer is connected at 60 kV at a 60/10-20 kV transformer station
- A-Low: The costumer is connected at 10-20 kV at a 60/10-20 kV transformer station
- B-High: The costumer is connected at 10-20 kV at a 10-20/0.4 kV transformer station
- B-Low: The costumer is connected at 400 V at a 10-20/0.4 kV transformer station

2.2 Disconnection risk vs. full access

The cost of connecting a heat pump depends on the type of connection. For full access to the electricity grid, the cost in Denmark is around 140,000 € per $\text{MW}_{\text{electric}}$. Another option is to get a discount where the district heating company only covers actual costs for the electricity company representing mainly the hours for administration and RTU[2] box necessary for monitoring and remote (simplified) control. This could instead cost around 30-40,000 € in total. In turn, the district heating company risk at all times to be disconnected from the electricity supply in case there is a shortage of power in the grid. Many Danish district heating companies have until now taken advantage of this solution to save on the heat pump investment costs, since the disconnection typically never occur. However, there is an focus on the stress of the electricity grid in some periods, thus indicating that the risk of being disconnected will likely increase in the future.

In any case, the cost for the district heating company also includes the electric cable. This should be taken into account when evaluating the most suitable POC.

2.3 THD

Electrical noise represented by Total Harmonic Distortion or (THD) as a result of the installation of large-scale heat pumps is to an increasing extent becoming an issue in Denmark and attracts attention from the electricity company often requiring an electric filter which represent an additional non-neglectable cost. The dialogue with the electricity company should be initiated early in the process to clarify necessary measures to be taken into account.

2.4 Electricity grid services

Besides optimising the heat pump operation according to the lowest electricity spot prices, the potential financial gains from supplying electricity grid services can be substantial. Regulating power (up/down) is a suitable area where heat pumps can play a role. In this case the flexibility and backup option of a thermal storage can be of extra importance[3]. However, in case of accepting a disconnection risk as described in section 2.2, it is not possible to offer extra regulating power (by lowering electricity demand for the heat pump) since this regulation option is considered already activated by the electricity company which is able to disconnect the heat pump if necessary.

It will likely be feasible to prepare the system for remote operation if the district heating operator wishes to outsource the activity of supplying electricity grid services. Heat pumps may also individually be too small (e.g., under 5 $MW_{electricity}$) to enter all markets but can be virtually pooled in order to enable additional market options.

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[2] Remote Terminal Unit

[3] See the document on “Configurations and energy system integration”.

When it comes to response time based on external signals, heat pumps are not as flexible as electric boilers. Hence, in a district heating perspective, the FRR as indicated in the table below, is more suited for electric boilers.

Abbreviation	Response time	Name
FRR	0.7-1.3 seconds	Fast Frequency Reserve
FCR (FCR-D, FCR-N)	30 seconds (5-30/150)	Frequency Containment Reserve (-Disturbance/-Normal)
aFRR	15 minutes	Automatic Frequency Restoration Reserve
mFRR	15 minutes	Manual Frequency Restoration Reserve

In many Danish cases, district heating plants invest in both heat pumps and an electric boiler simply to be more flexible – including in terms of such electricity service markets. Especially when a heat pump is already in operation and is able to adjust quickly (i.e., not having to perform a cold start), it may also enter frequency markets thus enabling additional revenues making the heat pump investment even more feasible for the district heating company and its consumers.

Figure 5. Small section of the electric hardware for a large-scale heat pump. Though the installation can be complex, the revenue from enabling optimized (possibly remote) operation may be substantial.