Final report

Experimental development of electrically driven heat pumps in the district heating system of Greater Copenhagen (SVAF)

Figure 1: SVAF heat pump

1. Project details

Project title	Experimental development of electrically driven heat pumps in the district heating system of Greater Copenhagen (SVAF)
File no.	64015-0571
Name of the funding scheme	EUDP
Project managing company / institution	HOFOR Fjernvarme P/S
CVR number (central business register)	26089263
Project partners	CTR, VEKS, DTU, TI, DME, Alfa Laval, Innoterm, HOFOR
Submission date	31 August 2023

2. Summary

UK: Large electrically driven heat pumps (HP) are expected to become central in the development of large CO2-neutral district heating systems as a supplement to biomass and for the integration of solar and wind power in the overall energy system The spread of large heat pumps also in the larger cities requires that a number of barriers are addressed and that operating experience is gained with large HPs under Danish conditions, including opportunities for optimization of operation and plant economy (scaling) in connection with the integration of the technology in district heating systems with the heat sources and coolants available in Denmark. This is investigated with several analyses, primarily based on the development and demonstration of a combined sea- and wastewater heat pump (5 MW).

DK: Store eldrevne varmepumper (VP) forventes at blive centrale i udviklingen af CO2-neutrale store fjernvarmesystemer som supplement til biomasse og til integration af sol og vindkraft i det samlede energisystem. Udbredelsen af store varmepumper også i de større byer, forudsætter at en række barrierer adresseres, og at der opnås driftserfaringer med store VP'ere under danske forhold, herunder muligheder for optimering af drifts- og anlægsøkonomi (opskalering) i forbindelse med integration af teknologien i fjernvarmesystemer med de varmekilder og kølemidler der er tilgængelige i Danmark. Dette undersøges med en række analyser som især baseres på udvikling og demonstration af en kombineret hav- og spildevandsvarmepumpe (5 MW).

Content

3. Project objectives

3.1 The objective of the project

Large electrical heat pumps (HPs) are viewed as an important part of diversifying and electrifying the district heating (DH) systems in Denmark. The aim of the project was to address the main barriers and further the use of HPs for DH through industrial cooperation, research and experimental development. The project has been the second phase of the SVAF project, where the first phase covered the development of an energy efficient design concept, the purpose of this phase was to invest, build and demonstrate the developed HP design in terms of system integration and cost efficiency cf. the overview below.

1. Develop feasible design concepts, controlling strategies and testing schemes (Finalized Phase 1 EUDP project ends Dec. 2015)

2. Detailed design, demo and monitoring of two promising HP concepts, research (This Phase 2 EUDP project 2016-2023)

3. Full-scale employment of HP in the Greater Copenhagen Area (GCA) (2021-2030)

When the project started out in 2015 the electric HPs faced several barriers preventing a large-scale introduction, including economic feasibility (in larger cities), lack of knowledge and operation experiences with large scale units, especially concerning large HPs using natural refrigerants (required by Danish law) and supplying heat above 70℃. The largest HP unit in operation in Denmark was around 1,3 MW heat production. Furthermore, experience with heat sources with a suitable energy potential for larger towns and cities was very limited and the main heat sources used where ground water and industrial excess heat.

Therefore, the partnership chose to focus on testing sewage water and seawater as heat sources with large energy potentials and available in most larger towns and cities. In terms of providing a base for upscaling the design to potentially 50-100 MW the HP was based on the largest ammonia compressors available that could at the same time provide temperatures of up to 90 C. The reason for testing this high temperature level, which was known to challenge the ammonia HP technology, was to investigate whether HPs could be seen as a stand-alone technology during the coldest part of the heating season or if it would be necessary to use other heat producing technologies as back up.

3.2 Which energy technology has been developed and demonstrated?

A demonstration HP has been developed, built, and tested at Sjællandsbroens pumpstation using ammonia HP screw compressors and based on sea and sewage water as heat sources. Another central technology choice was to test the use of plate heat exchangers for the two heat sources knowing this would be a challenge due to fouling. However, the upside of plate heat exchangers compared to alternatives, like tube and shell heat exchangers, regarding cheaper procurement, less uptake of space and not least better heat transfer and COP was an important part of the demonstration.

During the first phase of SVAF the partnership visited Helsingin Energia in Finland to see their largescale heat pump using sewage water. Their experience with plate heat exchangers was that even though they only cleaned the heat exchanges twice a year due to a limited maintenance budget, a reasonable flow was maintained. This indicated that an adequate heat source flow could be achieved with a more frequent but still acceptable cleaning frequency.

The SVAF test facility distinguishes itself from a commercial plant on two main points. First, the plant was built to test two different heat sources relevant for many urban areas such as the Greater Copenhagen area. Secondly, it has been equipped with many measuring units to collect as much data as possible for the test program.

WP2-4 on the establishment of a geothermal heat pump was cancelled and the project scope revised and approved by EUDP in 2019.

The change of scope was necessary due to major technical challenges in obtaining stable flow in the geothermal wells, which would require large investments to resolve and have a longer time horizon than the project's.

4. Project implementation

The SVAF project has provided all partners with a lot of valuable experience and knowledge on how to implement large electrical driven heat pumps for district heating. Even though large heat pumps for district heating have existed for many years in Sweden, Finland and Norway all of them have been running on other refrigerants and some that are not allowed in Denmark anymore and therefore large heat pumps on natural refrigerants for district heating purposes are developed and tested in the SVAF project. The project has encountered a number of challenges, some economic and organizational and other technical which a.o. have caused major delays, but also contributed to the learning process.

Below you will find important learning points, barriers/risks and recommendations in relation to the project implementation, based on an internal project evaluation workshop held in 2021.

4.1 Partners and responsibilities:

It is important to find equal partners in a project of this scope and large size, and all partners must have clear responsibility and a valuable contribution to the outcome of the project to ensure sufficient commitment.

- In addition, and this is not only for the SVAF-project, focus must be on:

- Type of project tendering being either single, multi or turn-key contracting to make sure that overall targets and demonstration value of the project can be met as good as possible also considering the partners and their role in the project.
- Roles and responsibilities – assess the partner's role and value, which can be both in the form of technology and knowledge, but also organizational set-up and deliverables
- Resources – are there employees with the right knowledge/skills and time for the project and does it match their role and importance for the project. The resource requirement for the project management role has been underestimated both in terms of the extensive time needed for taking care of the innovation partnership, project deliverables as well as EUDP administration and the decision-making process of the three DH company owners – CTR, VEKS and HOFOR. An estimated 1,5 full time employee for the project management job alone would have been beneficial. In addition, the role of Alfa Laval was also underestimated, considering the unexpected challenges with the heat exchanger and the heat sources.
- Commitment – it is important that the project is backed and prioritized by the top management at all partners.
- Solidity – is the partner financially and organizationally strong and large enough to undertake the tasks and responsibilities in the project, also considering the long-time commitment required as well as the relatively complex level of technical competences needed throughout the organization.
- Local representation – it is important that the partner is represented with an office providing O&M services and has both development skills and resources, and that there is a reasonable geographical proximity of the partner in relation to the implementation of the project.

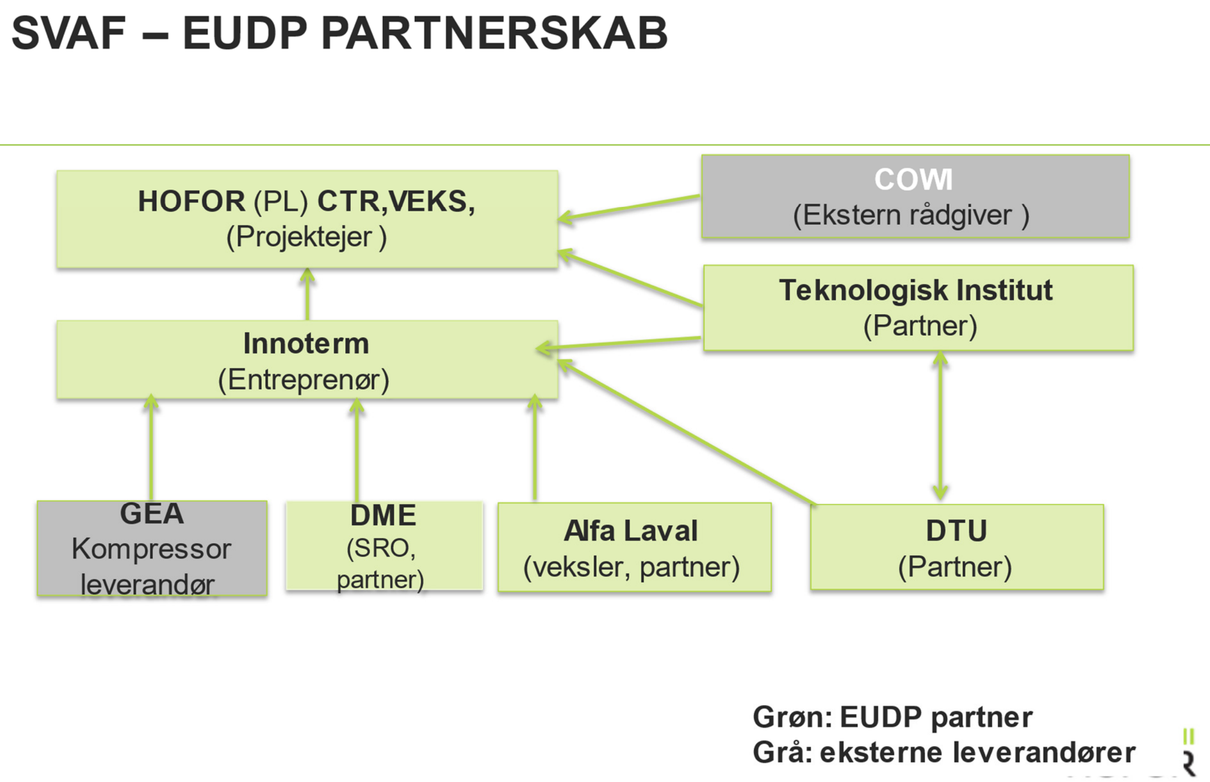

Figure 2: SVAF-project EUDP and external partners

Due to the rules of EUDP-funded projects it is difficult, to have consultant companies included as real partners, which could otherwise have provided valuable expertise and resources to a complex project like SVAF.

On the contrary EUDP rewards the involvement of smaller companies, and several smaller partners have also been involved in the SVAF-project. But due to the problems and delays in the project, they have been challenged on resources and finances. At the same time high requirements regarding i.e. financial solidity and dedicated number of employees could risk to rule out participants with valuable expertise, thus making it a complex challenge to find and include the right “small” partners in the right way.

4.2 Known Technology:

The starting point for SVAF was to make use of known technology and test it in relation to new system requirements (heat sources and district heating system).

However, despite the desire to primarily work with "known technology" at SVAF, and to focus more on upscaling of solutions, it subsequently turned out that the delivered heat pump had not been sufficiently tested with the chosen refrigerant (ammonia) at the chosen district heating specifications and temperatures, which unfortunately created a lot of unexpected problems and delays in the project. This also reflects that HPs for DH with the mentioned system requirements was a less mature technology at the time.

Some learning points and risks in relation to the project and choice of heat pump technology are:

4.2.1 Selection of screw compressors

- Choose largest possible units compared to natural refrigerants (scaling potential) but as the same time consider the advantage of a stepwise lift of the temperature to optimize COP.
- Go for known technology to the extent possible– with adequate specifications. HPs are complex systems to begin with and the more advanced and tailored a solution, the more difficult also to understand and fix the technical issues that arise. Furthermore, it was known that ammonia compressors would be challenged when demanding high forward temperatures – especially for the “ first generation” of HP compressors used at SVAF, that were originally designed for cooling and then refitted for heating purposed. Today a new generation of ammonia screws have been sent to marked designed specifically for heating purposes, although proof of concept still remains to be seen regarding stable forward temperatures of 90 C.
- Choice of test of flowrates and temperature span up to 90 C.

Rebuilt refrigeration compressors at high pressure stages have shown to cause major operational problems, but compressors built for delivering high temperatures were not available at the time. They are available today, but still need to deliver proof of concept.

4.2.2 Selection of plate exchangers

- The fouling risk of causing a lower COP was known but was increased by using the same plate heat exchanger for both heat sources (a cost reduction requirement). The consequence was that the two types of fouling enforced each other. This is however an issue specific to the SVAF project as most commercial HPs projects are based on only one heat source.
- The use of the same exchangers for sea and wastewater, also turned out to be a factor in relation to the choice of cleaning in place (CIP) methods:
    - Sea water is typically cleaned with acid (supplier specific product) on a regular basis and
    - Sewage water is typically cleaned with lye followed by acid on a regular basis

  Which means that there is an added complexity in the composition of the fouling material and cost in relation to keeping the heat exchangers clean.

4.2.3 Filter systems

- The design of sea water intake has not been optimal i.e. a coarse filter has not been installed. Furthermore, probably the intake has been dimensioned too small and is situated too close to the surface.
- The missing coarse filter (de-selected as part of savings exercise) caused many problems. The plan was to deal with cluttering from harbor material manually, however the need for manual cleaning was much higher than expected.

4.2.4 Choice of mobile CIP plant

- The solution was based on experience from district cooling but proved not to be sufficient at all. A built in CIP system, would have been the right solution.

4.2.5 Other savings exercises

- Reduction of technical building sqm, has made the operation and maintenance procedures in general difficult, including CIP.

Traditional (ammonia-R717) HP principle diagram:

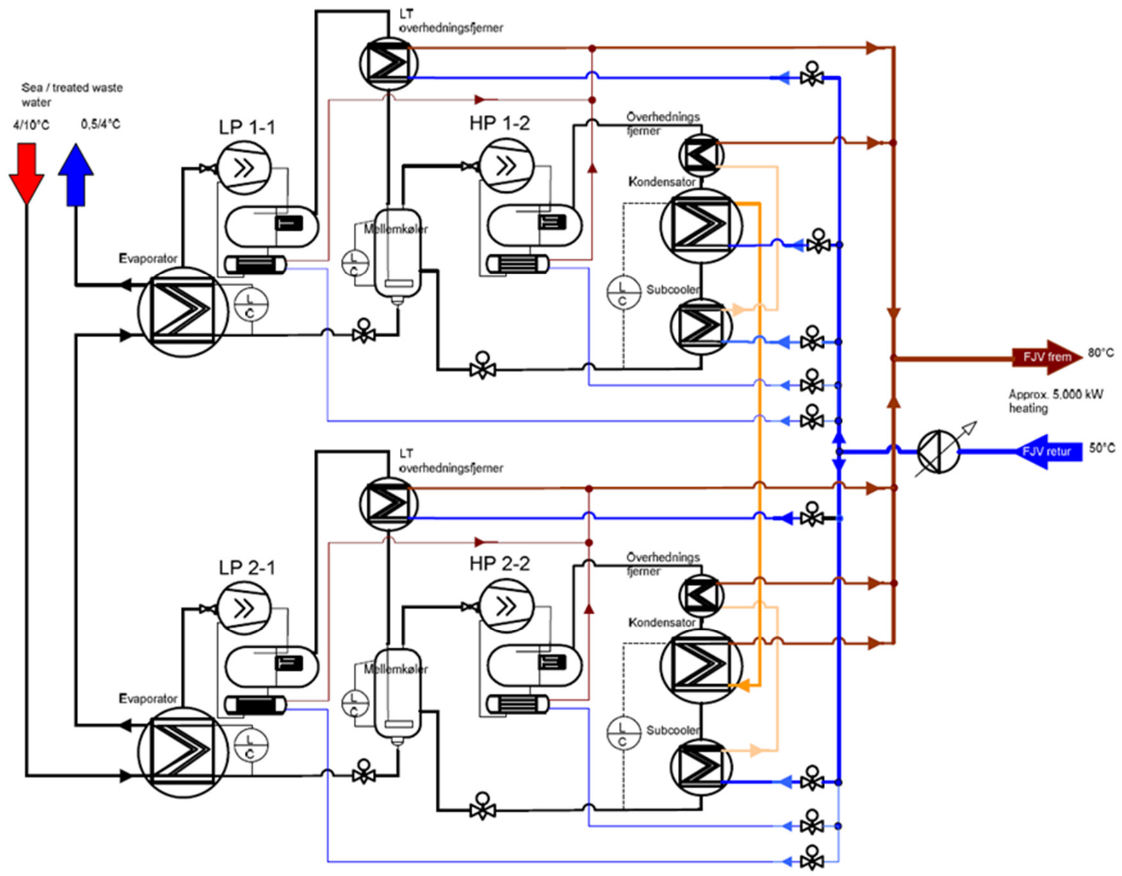

Figure 3: SVAF 2-stage heat pump design

4.3 Project implementation and organization:

Based on the evaluation workshop some important topics in relation to the project implementation and organization were also identified and discussed. The topics have been listed below:

- As project implementation form a multi-contracting solution instead of a turn-key solution was chosen, and this has a number of advantages and disadvantages that must be thoroughly risk assessed among the partners prior to entering into project contracts and agreements.

- Be prepared for and accept that development projects change over time and be ready to adjust the objectives.

- Early results in the project can be important to revisit later in the project, both because new knowledge can be gained, but also to ensure real use of the work. If a CIP facility and a regular CIP strategy had been in place at an earlier stage of the project, it could have changed focus and some of the results from the test program.

- The completed site visits in Sweden, Finland and Norway were not directly comparable with future facilities in Denmark, due to i.e., refrigerants used that are not legal or less known within the cooling sector in Denmark. In Sweden and Finland, they have used R134a (HFC-gas) which is not allowed in Denmark and in Norway they have used a HFO which was not allowed in Denmark before 2017, meaning 2 years after project start.

- Secure a good organization of the project with a broad-based Steering Group across the heating companies but remember also to get external sparring and knowledge from the Reference Group.

- It is important to continuously update the business case and the budget over the course of the project and as it has turned out especially on electrically driven heat production units like heat pumps where legislation in Denmark has changed dramatically in the last few years.

- Remember to pass on experience and learning to the entire relevant internal and external organizations as well as stakeholders.

- Create common share points for sharing documents with all relevant parties – preferable already from the beginning of the project.

4.4 Project cost and budget:

The business case and project budget has been a hard and instructive process and the project has suffered from budget increases on several occasions, which resulted in the saving exercises mentioned earlier. The HP Technology catalogue was used as a reference point (5 million DKK incl. connections) as there was no budget experience among the partners for an HP of that size of technology using the chosen heat sources.

An important leaning point was that balance of plant costs for HPs are very project specific and were highly underestimated at the time by the technology catalogue, which like the project, lacked sufficient references. Furthermore, additional costs must be expected in a demonstration project.

Realized investment budgets for HP projects have since shown that the heat pump only makes up 30-40% of the capital investment and thus HP investments are very dependent on local factors and vary a lot (4-15 Mkr. /MW). With two challenging heat sources, a high-temperature grid and a demonstration dimension, SVAF is at the more expensive end (15 Mkr. /MW) – on par with HPs estimated for geothermal energy in the Greater Copenhagen cooperation on geothermal energy.

In the light of hindsight, greater uncertainty should have been included in the budget from the start when it was a question of new technology application largely without references. Plants in Sweden and Norway are e.g., not comparable, and furthermore established by private companies that often do not share financial key figures. Projects regarding industrial surplus heat and groundwater heat pumps in Jutland, which were the most common at the time, were also not comparable to the chosen heat sources or to building costs in the greater Copenhagen area.

4.5 Site visits:

Site visits are important to learn from others and avoid mistakes by using the experience of other projects to prepare as well as possible for the project implementation.

The background for the visit to Oslo (HFO seawater heat pump) was to investigate this refrigerant whether it was more relevant than ammonia, and in addition to learn from their experience with seawater. The plant visit was planned in connection with HFO refrigerants being approved for large heat pumps in Denmark.

It was however concluded that knowledge about the advantages/disadvantages of HFO for district heating was too uncertain and no safer than ammonia. Lessons learned were reported to the steering group, and it was decided to continue with the selected plant design (detailed project).

The background for the visit to Stockholm Exergi (HFC seawater heat pump) was mainly to get input into the project's scale-up analysis (EUDP delivery) and to gain more knowledge about operation with seawater - also relevant for SVAF. The knowledge was not directly applicable to SVAF, but to future large-scale heat pumps and had to be reported in the project under the auspices of the scale-up analysis.

The project has been in dialogue with a number of other HP projects i.e., the sewage HP project in Kalundborg and Malmö, although due to differences in design and technology (other types of compressors or heat exchangers) most gained experience was not directly transferable. However, vibrations in the compressors stemming from various root causes leading to unstable operation or shut down has been experienced by several projects using screw compressors and in general these first generations of HPs for DH all experienced their part of operational challenges due to the immaturity of the technology for DH purposes, including lack of operational experience in the HP technology value chain.

5. Project results

5.1 Demonstration and test

Below is listed the deliverables from the EUDP application regarding work package 6 with the main emphasis on the results from the test program as enclosed in appendix 2, whereas the program and manual itself has been enclosed for inspiration for other HP development projects in appendix 3.

The short-term test program conducted by TI in cooperation with HOFOR during the periods, where the plant has been partly operational from January 2021 to May 2023. Due to the delays and challenges described in section 4 the long-term test program has only been carried out in parts. In total 10 different tests were run and some of them were conducted twice to confirm the results of the first test.

The short-term tests were divided into the following categories:

- compressors
- flow
- heat exchanger with refrigerant
- oil coolers

The goals of the tests were to observe the effects of specific parameter changes on the COP of the heat pump. The idea behind it was furthermore to see the potential for the use of HP autotune, a tool for automatic COP optimisation by changing selected control parameters of the system to reach the maximal COP. The tests were mostly conducted within one or 2 days per test, with as many changes of a specific parameter as possible. The plant was maintained running for about one hour with each new value after having reached a stable operation.

The first observation that can be made is the difficulty to be in “test conditions” on an operating installation such as SVAF. Indeed, the changes both on the source side and the sink side (DH) are highly influencing the COP and make it complicated to isolate the effect of the studied parameters.

To be free of these “effects”, a COP model was developed using operation data collected outside test periods to reconstruct an estimation of the “normal” COP levels for given conditions on the source and the DH side and compare this estimation with the “test” COP levels, measured during the tests. The model was purely statistical and gave a good estimation but with limited utilization range (only on the same temperature ranges as used to train the model) and was not considering other parameters that could affect the COP (heat exchanger fouling for example). An error of about ±5% between the measured COP and the estimated COP was obtained. It means that, when using this model to evaluate the tests, the differences under 5% cannot be attributed with certainty to the parameter tested.

The conducted tests didn’t show COP gains/losses outside of these ±5% interval. The comparisons between estimation and measurements are however presented in appendix 2 Analysis of SVAF II Short Term Tests but the conclusions are drawn using qualitative and quantitative observation on a more limited perimeter for each test. This also means that the use of HP autotune is compromised in regular operation of the heat pump since the effects on the COP of the changes in the control parameters (intrinsic to the system) cannot be clearly differentiated from the changes in the source or DH side (extrinsic to the system).

The results of the tests and thorough analyses of the data led to the following recommendations:

Test #	Tested parameter	Recommendation
3.3-1	Intermediate saturated temperature (HP1 & HP2)	Use the theoretical formula to estimate the intermediate pressure (and temperature) Decrease the intercooler temperature to the theoretical optimum for HP1: 32 ℃ (if supply temperature is maintained to 75℃)
3.3-2	Intermediate saturated temperature (HP1 & HP2)	Use the theoretical formula to estimate the intermediate pressure (and temperature) Decrease the intercooler temperature to the theoretical optimum for HP1: 32 ℃ (if supply temperature is maintained to 75℃)
3.4	HP1 setpoint temperature	Increase the setpoint at 53% to balance more the heat production of each heat pump in the total
3.5	Source flow (tested with sewage water)	Change the setpoint at the evaporators to about 4K
3.7	Flow through the desuperheater HP1-LS	Decrease the flow through desuperheater of HP1-HS to 16 m3/h or lower
3.9	Flow through desuperheater HP1-HS	Increase the flow through desuperheater of HP1-HS to 35 m3/h or above
3.10	Flow through desuperheater HP2-HS	Increase the flow through desuperheater of HP2-HS to the maximum possible (40m3/h)
3.14	Flow through oil cooler of HP2-HS	Increase the flow through oil cooler of HP2-HS
3.16	Flow through sub cooler HP2	Increase the flow through sub cooler HP2-HS to the maximum possible (25 m3/h or above)
3.17	Liquid level in separator HP1	Keep the liquid level in separator low, around 5% for example
3.18	Liquid level in separator HP2	Keep the liquid level in separator low, around 5% for example

Table 1: Test and recommendations

The values given for the flows in the heat exchangers are limited to the tested values, but lower or higher values could potentially be achieved after other changes in the system. The recommendations are also given with the COP as main driver. Some measures are also providing additional benefits, such as a lower refrigerant charge for the test 3.17 and 3.18.

5.1.1 Considerations on HP autotune and the potential for the heat pump

The “HP autotune” was developed to constantly maintain the maximum COP for the heat pump for all running conditions. From the test results the variation in overall COP while changing each parameter was very low. The heat pump installation showed surprisingly flat COP and was very independent on the adjustment of parameters. This indicates that there are little improvements to be gained by adjusting continuously the set points of diverse control loops. On the other hand, the test results showed where these set point should be adjusted to start with to gain maximum efficiency of the heat pump.

5.1.2 Considerations on HP doctor and the potential for the heat pump

The “HP doctor” was developed to monitor the status of the heat pump and send information to the operating staff around any changes in the heat pump operating conditions. The purpose was to investigate the cost efficiency potential of databased O&M as opposed to traditional O&M that is based on more general guidelines from the supplier. HP doctor is an analysis tool that will compare previously achieved key figures against those that the heat pump is currently running with. The measured values are kept in a database where key figures for the components being examined are stored together with operating data for the plant (see Figure). Therefore, no initial modelling and knowledge of e.g., dimensions are required.

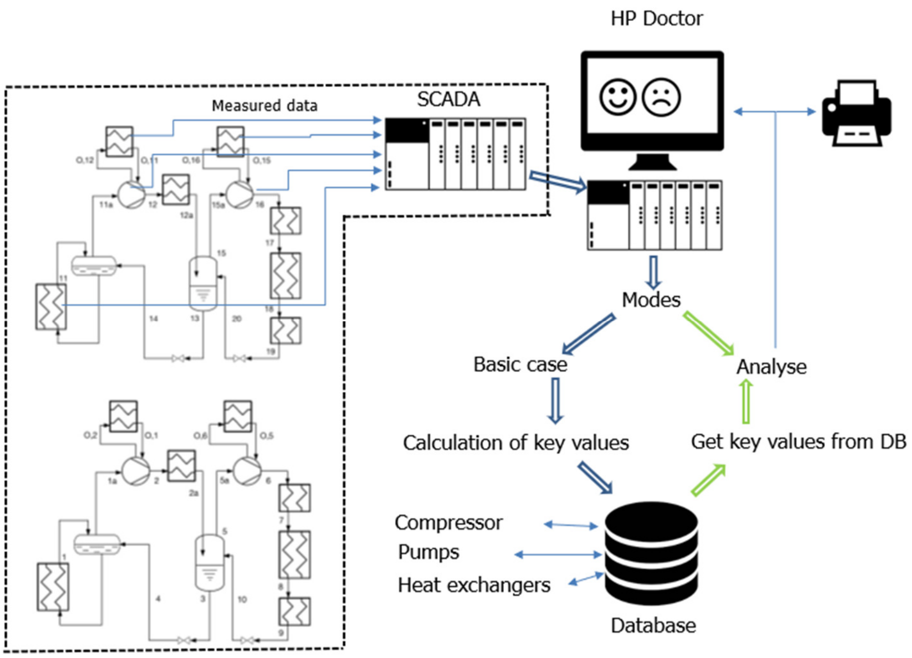

Figure 4: HP doctor layout

When the HP is running after commissioning, data is assembled in various running points within the HP’s operating envelope (the blue arrows). Several key figures are calculated for each running point when the system has been stable for a while and these numbers are stored in a database as a "Reference system" or as the plant's "Basic state".

When the HP is put into operation a diagnosis (the green arrows) is made by comparing new key figures with the "Reference system". If any of the ratios are worse than before, beyond a permissible difference, a notice is given to the operational personnel, indicating that that component needs to be examined further.

Because of a lot of delays in the project not enough long-term data has been available. The scattered data from previous periods will be used to test the HP doctor in connection with another EUDP Project (Digital

Twin).. The initial SAT (Site Acceptance test) data will be used as initial data and used to evaluate the later running conditions, especially around the fouling of heat exchangers and to see if HP doctor could predict the failures the system has experienced.

These results also allow to draw more general conclusions on the design of a heat pump for usage in other projects.

5.1.3 Operation and performance of the heat pump in the project

Apart from exploring the potential for COP and operational optimisations that can improve the resource efficiency and economy of largescale HPs, a general purpose of the project was also to test the maturity and operational stability of the technology. It was, and definitely still is important to know whether the technology is ready as a stand-alone alternative to large scale efficient combustion technologies, which still today deliver the main part of the base load production in larger cities.

Unfortunately, the project has faced many technical difficulties due to a.o. poor design and installation, others have pointed towards technological immaturity being very important knowledge for future large scale heat pumps.

Below follows a description of the more general status on the operation of the HP so far.

The HP is originally specified according to the below based on respectively sea water and sewage water as heat sources for a typical winter situation:

Performance data with sea water source 4 to 0.5°C and @ DH = 80°C:

- Cooling capacity: 3672 kW
- Heating capacity: 5194 kW
- Power consumption: 1635 kW (incl. losses in motors and frequency converters)
- Overall $COP_{heating}$ brutto is 3.2

Performance data with sewage water source 10 to 4°C and @ DH = 80°C:

- Cooling capacity: 3732 kW
- Heating capacity: 5177kW
- Power consumption: 1552 kW (incl. losses in motors and frequency converters)
- Overall $COP_{heating}$ brutto is 3.3

Table 2: Performance target data of the HP for the SAT test.

In March 2019 a system acceptance test (SAT)[1] of the heat pump was carried out on both heat sources with the following acceptable results.

2.7 - District heating capacity limit

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	Start	Finish				
Date: 19/3/2019 & 14/3/2019			Time			
Adjustments	**Sensor**	**Design**				
Max test	14-03-2019		**12:36**	**12:53**	**13:21**	**13:36**
District heating inlet temperature	TT4250	50°C	50,4	50,1	50	50,1
District heating intermediate temp.	TT4257	68°C	66,3	65,6	66,6	66,6
District heating outlet temperature	TT4223	80°C	79	78,7	78,3	78,7
COP varmepumper			2,91	3,02	3,09	2,72
Heat pump system load (max)	02EM4262	5200kW	4700	4900	5000	4700
Average COP_H over one hour			2,99			
Heating average load over one hour			4830			
Min test	19-03-2019		**15:36**	**15:48**	**16:04**	**16:27**
District heating inlet temperature	TT4250	50°C	45,6	45,6	45,1	44,7
District heating intermediate temp.	TT4257	68°C	69,6	69,3	69,4	69,3
District heating outlet temperature	TT4223	80°C	79,9	79,5	79,9	79,9
COP varmepumper			2,97	2,88	3,01	2,99
Heat pump system load (min)	02EM4262	Min	3100	3000	3100	3000
Average COP_H over one hour			3,05			
Heating average load over one hour			2930			
Source			Seawater			

Accepted	X

Comments:

We use the values we got from the performance test for seawater as max and run the min capacity with seawater. The min capacity is reached as the lowest value where the heat pumps can run stable.

Table 3: SAT-test for sea water – March 2019

[1] Appendix 1: SAT test results

2.2 - Performance test - Sewage water

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	Start	Finish				
Date: 19/3/2019	12:04		Time			
Adjustments	**Sensor**	**Design**	**12:36**	**12:53**	**13:21**	**13:36**
District heating inlet temperature	TT4250	50°C	50,1	50	50,3	50
District heating outlet temperature	TT4223	80°C	80	79,6	79,9	80,3
District heating flow	FT4261	140.7	129,6	133,2	142	138
Sewage inlet temperature HP1	TT4127	7	7,9	7,9	7,9	8
Sewage outlet temperature HP1	TT4128	4	5,2	5,2	5,2	5,4
Sewage inlet temperature HP2	TT4125	10	10,7	10,8	10,8	10,8
Sewage outlet temperature HP2	TT4125	7	7,9	7,9	7,9	8
Sewage flow to evaporators	FT4162	529.2	568/524	559,/518	574/532	5767531
Requirements						
Total COP_H minimum (0 -> -9%)		3,08 to 3,38	3,11	2,94	3,49	3,19
District heating load (0 -> -5%)		4480 to 4716kW	4500	4600	5500	5000
Average COP_H over one hour			3,14			
Heating average load over one hour			4880			

Accepted	X

Comments:

VP1 LP is on suction pressure load inhibit. VP2 LP is in discharge pressure load inhibit. Filter on the sewage water site cleaned at 13:17.

Table 4: SAT-test for sewage water – March 2019

However due to the many technical difficulties and break downs of the HP, after the SAT-test, it has in general unfortunately been impossible to verify these performance figures in the EUDP project in situations with long term stable operation. This is of course a very important issue and crucial for the overall business case and will be pursued by the main partners in the future operation of the HP.

However, for sewage water as a heat source the project has been able to carry out a short term tests indicating that a heating capacity of 5 MW, COP of 3,5 and district heating supply temperatures of 70 degrees can be reached with sewage water temperatures of around 12-14 degrees as illustrated below.

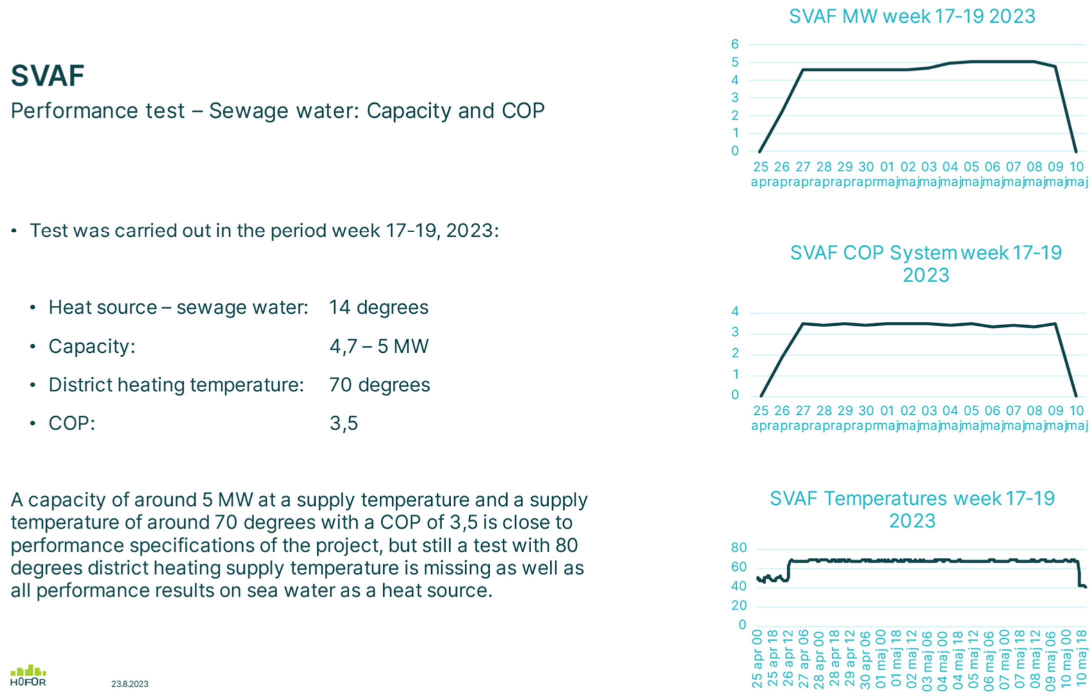

Figure 5: Performance test – Sewage water 2023: Capacity and COP

The test with a district heating supply temperature of 80 degrees still remains to be carried out.

Furthermore, a short-term maximum temperature test verified that the HP can reach a district heating supply temperature of 90 degrees during the winter season where source temperatures are at their lowest.

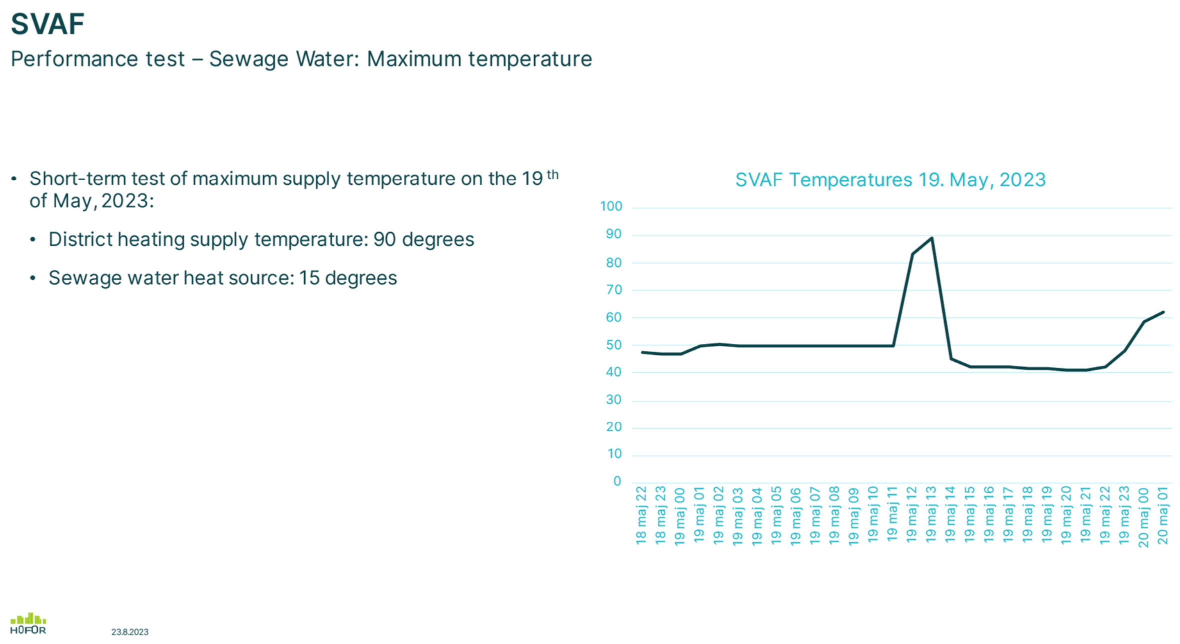

Figure 6: Performance test – Sewage water 2023: Maximum supply temperature

Further performance tests will be carried out as soon as we have a stable situation on operation and maintenance of the HP and the source and demand side are at their operational borders, like sea water at 4 degrees or below and district heating supply temperature of 80 to 90 degrees. However, based on the experience from the completed test program and the latest operation performance it is expected that the HP will attain a normal level of operation in the year to come.

The design of the SVAF HP was deliberately not optimised for delivering services for the power market[2] because it was estimated by TI that it would be too expensive and complicate the design further. Furthermore, the objective of SVAF was to build and demonstrate a stable and optimized large scale heat pump to participate in the Greater Copenhagen heat market alongside other base load heat productions units.

However, the intention was also to explore in general what possible system services if any could be delivered from an HP system optimised towards being an optimal base load DH production unit. Based on SVAF and the selected screw compressor technology it seems unlikely to be able to provide system services to the power market, due to very slow start/stop and reaction times. Experience from other larger heat pumps like the FlexHeat[3] groundwater heat pump with piston compressors it seems that by designing and specifying correct there should be possibilities to offer i.e. mfrr, afrr and even fcr-n to the power market, however this has not been fully documented yet. Also heat pumps with turbo compressor seem to have the technology for offering system services to the power market, but it also here remains to be seen.

5.2 Business case and dissemination

The legal framework has in general in Denmark as well as in the rest of Europe over the last couple of years developed in a direction where electricity from wind and solar has rapidly developed into being the most sustainable and cost-effective energy source for heating solutions and has thus paved the way for much more heat pump capacity in the district heating sector in Denmark.

[2] https://energinet.dk/el/systemydelser/introduktion-til-systemydelser/oversigt-over-systemydelser/

[3] https://www.hofor.dk/baeredygtige-byer/udviklingsprojekter/fremsynet-fjernvarme/flexheat-intelligent-varmepumpe-i-nordhavn/

The business case is typically positive if you have an available free heat source, sufficient affordable land, an electricity grid with the needed capacity and a low temperature district heating system nearby.

For the Danish market the development of large heat pumps for district heating has been increasing rapidly in capacity since 2020 and especially in Jutland where land typically is not that big a problem as in the greater Copenhagen area.

The dissemination of large heat pumps in Denmark is already happening and will over the coming years only intensify, as it can be seen in the below figure and table:

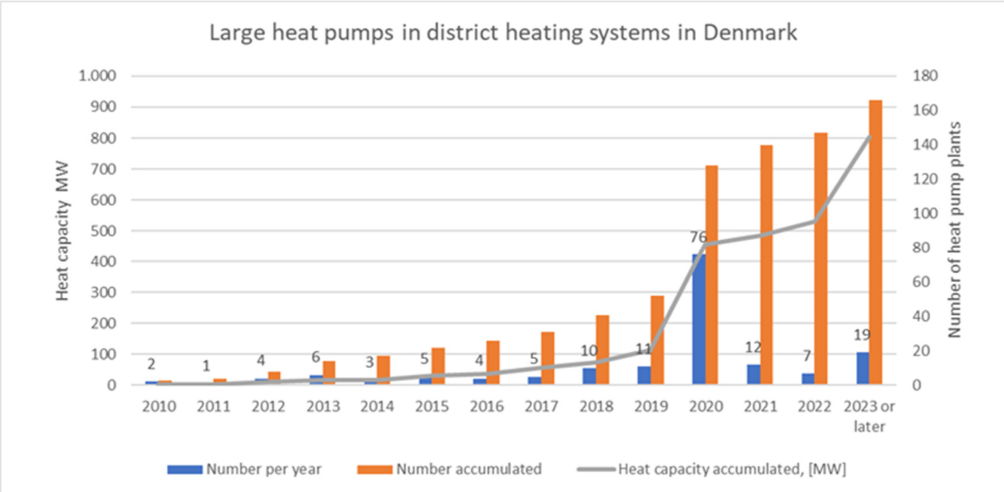

Figure 7: Large central heat pump installations in Denmark (Source: Dansk Fjernvarme/Aug. 2021)

Year	Number per year	Number accumulated	Heat capacity accumulated, [MW]	Average HP size, [MW]
2010	2	3	1,7	0,6
2011	1	4	2,2	0,5
2012	4	8	11,5	2,3
2013	6	14	16,5	0,8
2014	3	17	17,8	0,4
2015	5	22	30,7	2,6
2016	4	26	35,6	1,2
2017	5	31	55,4	4,0
2018	10	41	74,0	1,9
2019	11	52	113,3	3,6
2020	76	128	455,8	4,5
2021	12	140	484,0	2,6
2022	7	147	529,5	7,6
2023 or later	19	166	804,3	14,5

Table 5: Large central heat pump capacity installed year-by-year (Source: Dansk Fjernvarme/Aug. 2021)

Air to water heat pumps is by far the most widely used with appx. 80 pcs. followed by waste heat heat pumps with 22 pcs in Denmark. Large sea water heat pumps are also in the pipeline in cities like Esbjerg (50 MW), Aalborg (100 MW), Copenhagen (30 MW) as well as a 100 MW large geothermal heat pump in Aarhus but are not yet build and/or in operation.

5.3 Deliverables

5.3.1 Obtained commercial results.

The potential for optimizing COP has been at the heart of the project to increase the cost efficiency, resource efficiency and competitiveness of large-scale HPs.

The results of the test program point towards the fact that the largest COP potential lies within optimisation of utilizing the heat source as well as the integration with the DH net.

Furthermore, issues with compressors less suitable for delivering high forward temperatures at SVAF and other HP facilities, has demonstrated a need for developing and standardizing ammonia compressor technology to meet system requirements in larger DH nets during the winter season. During the project period the HP manufacturers and suppliers have recognized this need and larger units targeting higher temperatures have been made shelf ready. However, proof of concept in specific DH networks is still to be seen.

As for the commercial result for the specific test HP, the partnership has developed an efficient HP facility capable of delivering a satisfactory COP, when the conditions for the heat sources are operational. Due to the extra costs of developing and building a test HP, SVAF is not estimated to obtain a positive business case over the expected 20-year period of operation and the most likely scenario is that part of the investment will not be returned to the three DH companies.

5.3.2 Unexpected results.

In 2017 the use of HFO refrigerants for large scale HPs were permitted by the Danish Environmental agency and hence a study was performed by DTU comparing ammonia with HFOs that was not planned from the beginning. However, since EUDP is planning to phase out all flour-based refrigerants these results are deemed less relevant for future projects.

Other learning points from the project that were not planned from the beginning have arisen from the process of building a new production technology, including investment costs and footprint requirements and finally the maturity of the technology (lower than expected) in combination with the complexity of an HP system on an industrial scale. When the project was starting out, the barriers to introducing Large HPs was generally viewed as a question of reducing power taxes and the technology was addressed as known technology that just needed a little adjustment to fit DH purposes. Especially, the challenge of finding suitable energy sources as well as solving the technical barriers involved in exploiting them was highly underestimated. The same goes for the development and optimisation of ammonia HP systems. It was i.e. chosen not to have a compressor supplier on board in the partnership, because this was seen as state of the art and the purpose of the project was to test how far state of the art had come expecting that it had come further than it turned out. The challenge of applying a tailored solution as opposed to off-the-shelf products has also been a learning point from dialogue with various suppliers along the way. When the project was starting out mainly international suppliers could deliver off the shelf large scale HP units however these solutions were not applicable to the Danish market due to the use of other refrigerants and limitations on forward temperatures.

When giving presentations during site visits and in various DH fora the project has been highlighting these challenges and the need for working on solutions and sharing knowledge across the HP and DH sectors.

5.3.3 Target group and added value for users.

The target group for the results of the project are other DH companies and organizations involved in heat supply from large scale HPs. Furthermore, technology developers and suppliers, including manufacturers, contractors, consultants, and academia can also benefit.

The mission of the project was to demonstrate the performance of HP technology available at the time, which turned out to be immature in some respects. At the same time integration of the HPs with DH systems was new to both DH companies and HP suppliers. Hence the project has pointed towards requirements for HP technology and design improvements but not a new or patent specific product as such.

However, the project has with the assistance of DME, TI and DTU created two prototype tools for operational optimisation with elements of machine learning: The HP autotune and the HP doctor.

So far, the test program has shown that the continuous adjustment of compressor operation has low impact on COP and therefore the potential of HP autotune is also estimated to be marginal.

The HP doctor in the other hand could still prove to have potential, but due to limited hours of operation on the test HP the amount of data is too limited to draw conclusions. Although this will be possible within a year or two, when enough data has been collected after the HP has started commercial operation. Those results will however not be possible to fully include in this project but may be included in other studies without interfering with the commercial operation of the HP as such.

5.4 Assessment of heat pump potential in Greater Copenhagen

The purpose of this analysis from 2020 was to assess the energy potential (MW) of heat sources for large HPs in Greater Copenhagen area within the distribution areas of CTR, VEKS and HOFOR. The analysis is subject to changes already, due to major changes in potential, legislation and energy prices since 2020. Heat pumps need a heat source from which energy can be absorbed. This can, among other things, be ground heat or air, which is known from smaller individual heat pumps for the supply of summer houses and individual buildings. When it comes to large-scale heat pumps, here defined as > 0.5 MJ/s, for district heating supply, it could be the same or many other heat sources, but it is required that the available heat sources have sufficient flow and temperature level to keep the heat pump in operation throughout the whole year with a reasonable coefficient of performance (COP).

The analysis focuses on low-temperature heat sources such as sewage water, sea water, drinking water and ground water, i.e., not geothermal, and excess heat. Air as a heat source for large heat pumps is also not included, due to too low supply temperatures in winter, when the heat demand is greatest, as well as challenges in complying with noise requirements in a dense urban environment.

The mapping shows that there is great potential for heat pumps to become a central part of Greater Copenhagen's heat supply, but it is a prerequisite for the realization of this resource that the financial and planning framework is present. Based on key parameters, it has been assessed how large the technical capacity potential is, considering the energy content of the heat source, proximity to the district heating network, physical network limitations to remove the heat, as well as sufficient land/space conditions with a view to establishing a heat pump central.

It is important to note that the realization of this potential also depends on the competitiveness of the heat pumps in relation to the other available energy technologies and on the need for new production capacity in the district heating system. In particular, the question of the expansion and maintenance of the existing cogeneration plants in the capital area, as well as a possible development with geothermal energy can affect the development rate of large heat pumps with low-temperature sources. In addition, there is the possibility of delivering to low-temperature district heating areas, which can be decisive for COP and economy.

The table below shows an estimate of the total capacity potential that is assessed as realizable in the Greater Copenhagen area, if heat pumps based on low-temperature sources become a competitive technology, and where only the overall capacity requirement in the district heating system is considered.

2035

Potentiale MJ/s	CTR	HOFOR	VEKS	I alt
Spildevand	6	41	27	74
Havvand	0	60	20	80
Drikkevand	25	35	5	65
Grundvand / ATES	30	20	40	90
I alt	62	156	92	310

2050

Potentiale MJ/s	CTR	HOFOR	VEKS	I alt
Spildevand	6	41	27	74
Havvand	0	420	20	440
Drikkevand	25,4	35	5	90
Grundvand / ATES	30	30	90	150
I alt	62	526	142	754

Table 6: Heat pump potential in Greater Copenhagen area in 2035 and 2050.

The potentials are indicated for two years in the medium and long term, because it takes time to develop such new energy supply solutions, which represent a larger number of geographically dispersed construction projects. The above is a simple proposal for a possible expansion, up to 2035, and is based on possible projects, some of which are at conceptual level, while a smaller handful have been established or are being established. In the period between 2035 and 2050, there is an expectation that it is feasible to establish an additional 360 MJ/s seawater heat pump, located close to the coast to Øresund in the Copenhagen area.

In addition, there is an expectation of an increased need for ATES plants, especially in the VEKS supply area, corresponding to an expansion effect of 60 MJ/s heat pumps. This assumption is based on the fact that in VEKS' area there is a coincidence between a larger number of industrial companies with cooling needs and better space conditions than in very densely built-up areas.

A period of overcapacity may not be avoided if sufficient power from heat pumps is to be established towards the end of the 2020s to compensate for parts or all of the phasing out of the large co-generation units that are expected to take place in the 2030s.

In the following, the most important conditions for the utilization of the various low-temperature sources are summarized.

5.4.1 Sea water

As can be seen from the table above, sea water is the one of the low-temperature sources with the absolute greatest energy potential, and also a much greater technical potential than indicated in this calculation. In Varmeplan Hovedstaden 3[4], it was stated as being infinite, as the water in the Øresund is an inexhaustible resource. The potential for seawater heat pumps is based on the coastal resources. This is due, among other things, to the costs of extracting the resources far from the coast.

[4] https://varmeplanhovedstaden.dk/om-projektet/materiale-fra-vph3/

This report disregards harnessing heat from the Hollænder Deep (between Middelgrund and Saltholm), 5-6 km from the coast, deeper and wider than the Konge Deep. Due to the distance to the coast and the fact that it will be necessary as a first step to gain experience on the basis of more coastal resources.

If it turns out, in a number of years, when there is experience with seawater heat pumps that utilize more coastal water, it can be economically sensible to include remote areas in Øresund, and then the potential will be able to be adjusted upwards.

5.4.2 Wastewater / sewage

For wastewater, the uncertainty in the potential assessments is considerably less, as our knowledge of this resource and its development is more exact. Here, the uncertainties are to a greater extent connected with the specific construction areas availability, which depends on available space at the existing treatment plants, ownership, neighbors, as well as the fact that there are ongoing considerations to move the largest of the treatment plants in Copenhagen, such as will be necessary if the plans for Lynetteholmen, a larger filling and expansion of Refshaleøen become a reality.

Heat pumps based on wastewater seem to be economically viable and will be able to compete with biomass cogeneration. However, there are still operational challenges with wastewater heat pumps, i.a. because biofilm from the bacteria in the wastewater can reduce the heat transfer in the exchanger and thus reduce the efficiency of the heat pump. However, provided sufficient operational experience is gained combined with maturation of the technology, it is expected that wastewater will be the most profitable low-temperature source. This is due to the high temperatures in winter (min. 10 C) as well as the possibility of utilizing large-scale benefits at the outlet from the treatment plants, where large amounts of sewage water are available. Compared to sea water, the energy potential is still relatively limited.

5.4.3 Drinking water

The technical potential for utilizing drinking water with a heat pump is not subject to such great uncertainty, as the availability and quantities of the heat sources are not expected to change significantly over time. However, it must be investigated in more detail to what extent the flow is reduced at night, when consumption drops. When utilizing the heat source from drinking water, it is necessary to insert an intermediate circuit between the heat source and coolant for the sake of drinking water safety, which results in a heat loss that affects the COP in a negative direction. In addition, cooling the drinking water will result in increased electricity consumption for reheating domestic water for e.g., baths, washing machines, cooking, etc. There are few connection points with larger capacity and therefore only a few plants can benefit from these.

5.4.4 Groundwater

The potential for using groundwater as a heat source is, in principle, great, but depends to a large extent on project-specific conditions and can therefore best be assessed on a project-by-project basis. The potential for 2035 is therefore to a certain extent, especially towards 2025, based on already realized projects and project opportunities that the utility companies are aware of. Several of these will probably not be realized. On the other hand, others will probably appear.

In dense urban areas, groundwater systems are typically used in the form of ATES systems to supply individual buildings such as hotels or hospitals with both heating and cooling. No references have been found for installations over 4 MJ/s and the challenge of scaling up groundwater heat pumps further is that the required number of boreholes is difficult to find space for in dense urban areas. In addition, there is consideration of drinking water interests and any treatment requirements in relation to sending the water back to the underground. The possibility of using groundwater as a heat source in dense urban areas is therefore considered limited compared to the other heat sources.

5.4.5 Important factors for the economy of large heat pumps

Large heat pumps are a new technology in large Danish district heating systems and therefore there is uncertainty about the realization of the technical potential, which depends on the technology being competitive. There are a few key factors that are of great importance to the economy and the spread of heat pumps based on low temperature heat sources.

The first parameter is the electricity price, which makes up the largest part of heat pumps' operating costs. The price of electricity is highly fluctuating, and this trend is expected to increase in the future, in line with the spread of solar and wind energy. For the heat pumps to have many operating hours in the district heating system of the future, it is important that they can take advantage of the varying electricity prices and produce the heat when the electricity price is low.

Another key parameter is the investment costs for the facilities themselves, which constitute a large financial item. It is important to try to reduce these costs by e.g., to have the facilities located close to the heat source and district heating network and, if possible, by scaling up the facilities.

The COP value for the production is another decisive factor to have an attractive plant with a good operating economy. This must be ensured by locating the most attractive heat sources, with the highest possible temperatures in the heating season, combined with efforts to lower the supply temperature in the distribution networks. This is continuously being worked on in the capital area, but it depends to a large extent on the condition of the district heating customers' heating installations, and with many thousands of customers in the Greater Copenhagen capital area, it is a long-term effort. Urban development of urban areas where low-temperature district heating can be established from the start like Nordhavn and Lynetteholmen are obvious options in combination with large heat pumps in the future.

The below table illustrates the importance of heat sources in combination with the supply temperature to the district heating network for the COP of the heat pump. This however cannot be directly linked to the price of district heating due to very large differences in the investments for being able to utilize the available heat source.

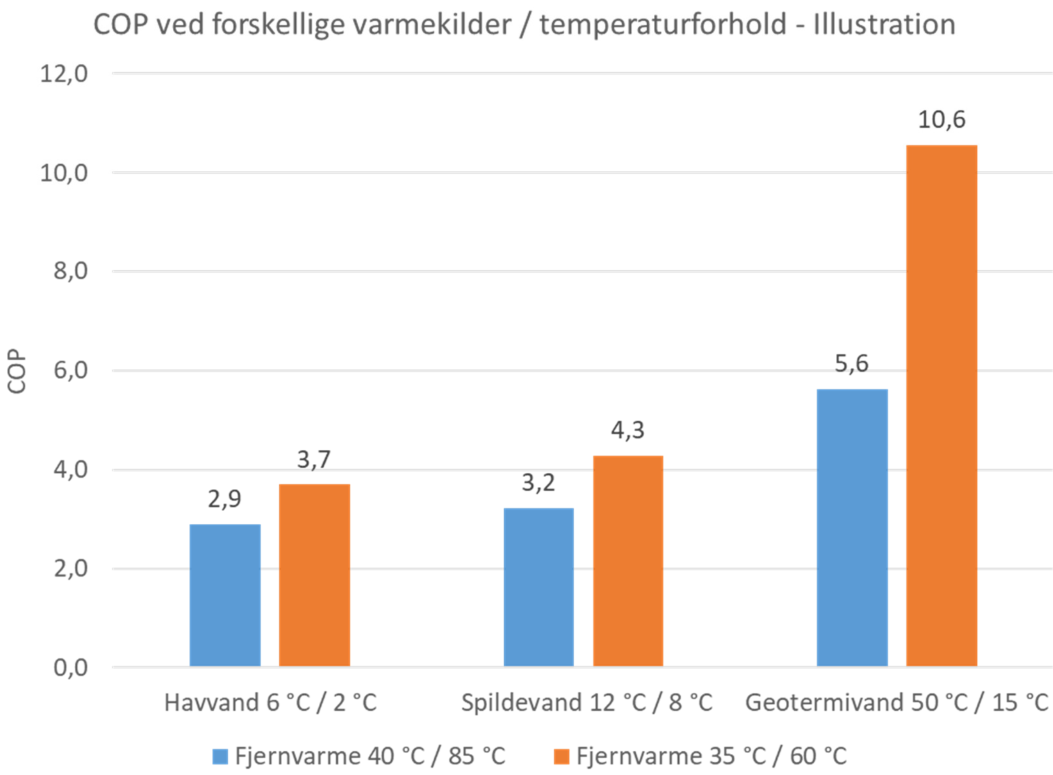

Table 7: Heat pump COP at different heat source and district heating temperatures

The last parameter, which is of great importance to the economy, is the heat price the heat pumps can get for their delivery to the district heating system. This is not something that the individual heat pump project can influence, as this depends on the development of the competing technologies, such as cogeneration plants and geothermal energy, and not least on the capacity requirement in the district heating system. However, knowing that the pace of expansion is spread over a long period of time and over many different plants, where the power requirement at the relevant location in the district heating network should be assessed in each individual case, should be able to minimize the risk of wrong investments and overcapacity.

In addition to these considerations, some generic business case examples have been calculated, which give some indications of what is needed to achieve a reasonable economy in a heat pump project for district heating. Using a model of the district heating system as well as the Nordic power market (the BALMOREL model) it has been calculated how many hours of operation an HP achieve based on the COP regardless of choice of heat source.

These calculations indicate that in order to attain a reasonable number of operational hours for the investment to be returned an HP based on low temperature heat sources (4-20 C) should at least achieve a COP of 3.

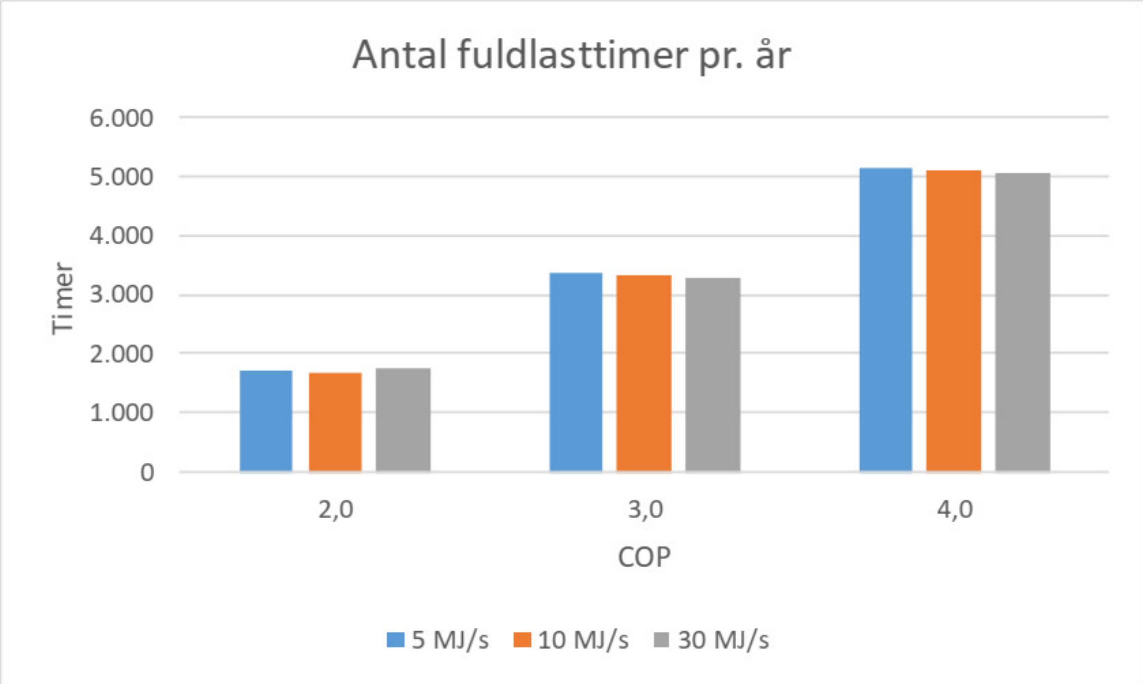

Table 8: Heat pump COP at different heat source and district heating temperatures

Furthermore, the table below gives an indication of the relation between COP and break even attained in terms of investment in Mio. DKK per MW heat production.

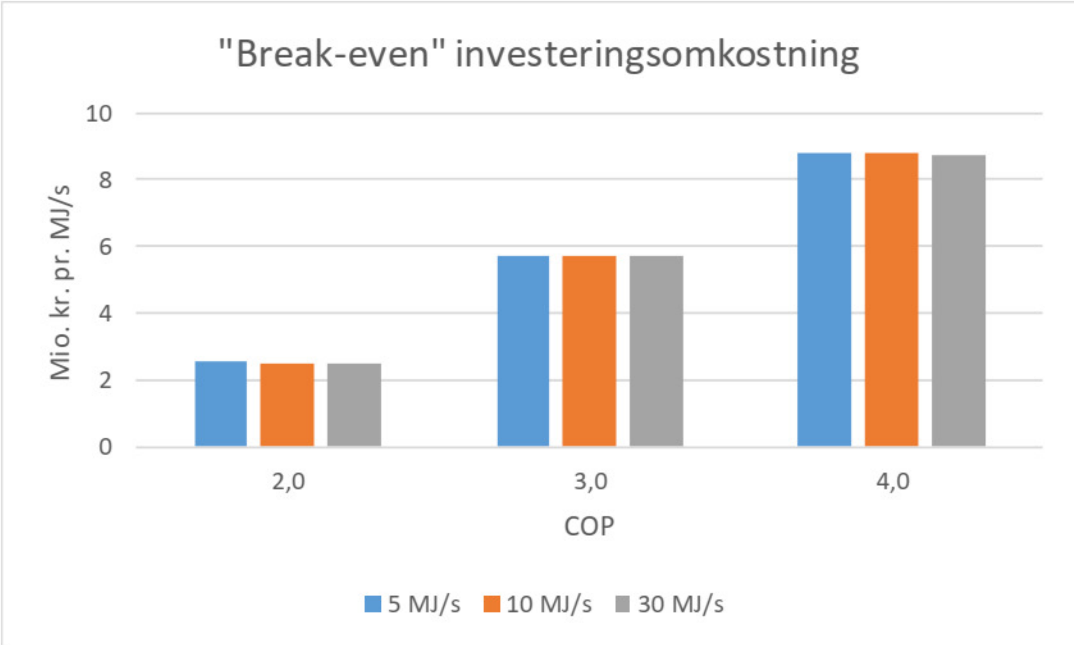

Table 9: Heat pump COP at different heat source and district heating temperatures

5.5 Study of upscaling Heat Pumps

The purpose of the scale-up analysis of large heat pumps for district heating is to contribute knowledge, experience, and recommendations from the SVAF project to other large heat pump projects.

Since the SVAF project started in 2015, where the starting point was Varmeplan Hovedstaden 3[5] from October 2014 and a scenario with approx. 300 MW heat pumps in the capital area in 2035, the potential and issues surrounding both heat sources and scaling up have changed significantly.

For example, the vision project "the Future District Heating in the Capital Region 2050 (FFH50)[6]" from 2021 has shown that the realistic potential for heat pumps towards 2050 is up to approx. 1,200 MW.

However, there are many criteria, both technical and natural, which must be met to even talk about large heat pumps in district heating - and in particular in the metropolitan area.

Firstly, in many cases and for several heat sources, it will not be possible to scale up heat pumps to the extent that was assumed, because the energy content of several heat sources such as e.g., wastewater, excess heat and groundwater set a natural limit for the effect that is available at the individual location and thus also for the size of the heat pump.

However, seawater heat pumps are the exception, which seem to be able to be scaled up on a large scale in areas out to sea with great depths, such as e.g., on the existing power plant sites, but also remains an area

5 https://varmeplanhovedstaden.dk/om-projektet/materiale-fra-vph3/
6 https://varmeplanhovedstaden.dk/

where there is a need for technical development and testing of solutions on a large scale before a larger rollout can take place in the capital area.

Another limitation for large heat pumps in the district heating system is partly the high temperatures in the transmission networks, where today, temperatures above 100 C are required, and partly the physical limitations on how much capacity can be supplied in the individual district heating distribution networks (typically around 30 MW) which in terms of temperature are more compatible with heat pumps.

In addition, there has been a development within the standardization of the heat pump suppliers' products towards larger units and combined with the possibility of building heat pump plants of several units in series and/or parallel configurations, which with the larger unit sizes available means that 50-100+ MW plants will be established with possible large-scale benefits within reach.

However, there is still a long way to go in terms of gaining experience with larger plants on different heat sources. So, gathering practical experience and sharing knowledge across the industry is still crucial to optimizing the technology and its competitiveness.

Along the way, it has also been learned that many more factors than technology and scaling are important for the roll-out and competitiveness of large heat pumps.

Therefore, the analysis has also gained a broader focus on what is needed to roll-out large heat pumps, and not just in terms of technology development and economics, but also in terms of handling energy sources, areas, sector coupling, etc.

The analysis is based on the Greater Copenhagen area and CTR, VEKS and HOFOR's district heating supply areas. But all the reviewed criteria for realizing large heat pumps are of a generic nature and thus also applicable to larger district heating cities in the rest of Denmark and in principle also to all other markets.

5.5.1 Potentials and heat sources:

In the project FFH50, which was a collaboration between CTR, VEKS, Vestforbrænding and HOFOR, a total technical potential for heat pumps in the metropolitan area (at distribution network level) was estimated at approx. 2,100 MW in 2050.

However, due to overlap in the heating base and competition for the various heat sources, physical limitations for location as well as the possible uptake in the capital area's district heating distribution system, the realistic technical potential is estimated at approx. 1,200 MW towards 2050.

The existing base load capacity in the district heating in the capital area is in 2021 approx. 2,200 MW, and thus there is considerable potential for large heat pumps towards 2050.

An example of the potentials as well as the conflicts between the different heat sources can be seen from the 2 below figures indicating possible suitable areas and heat sources available in the Greater Copenhagen area.

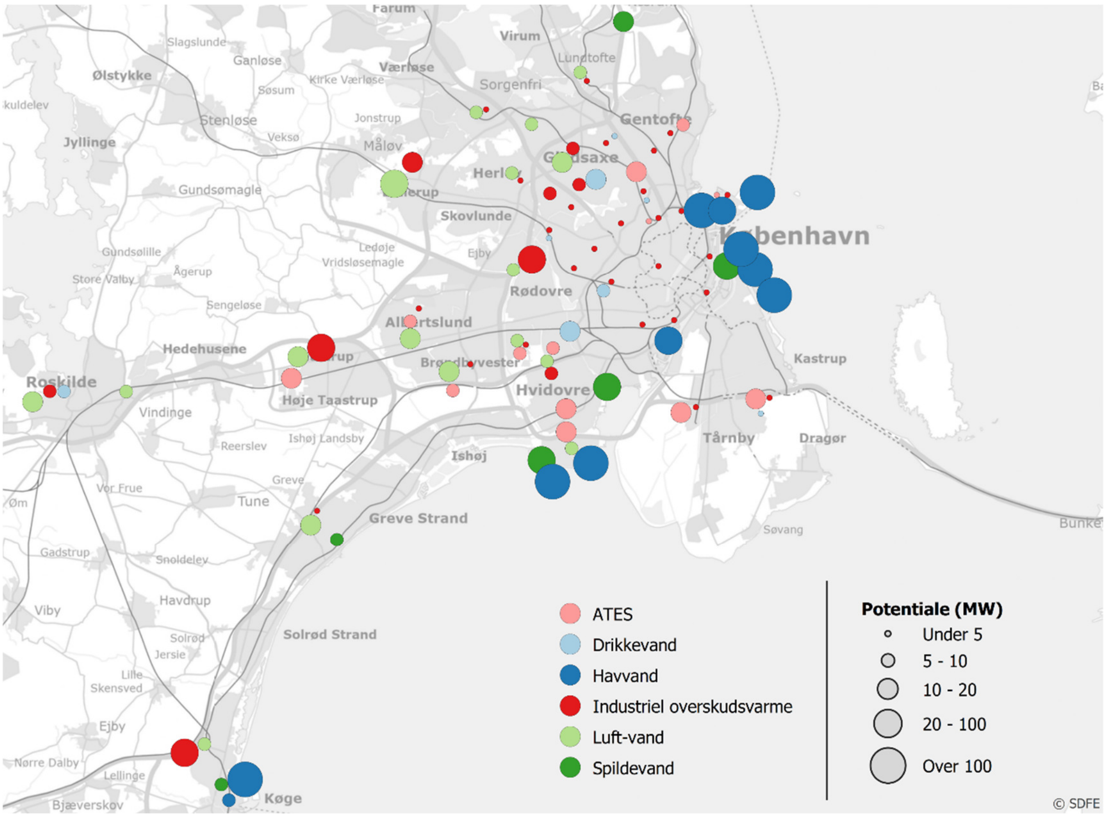

Figure 8: Possible heat sources and suitable areas excl. geothermal in the Greater Copenhagen area

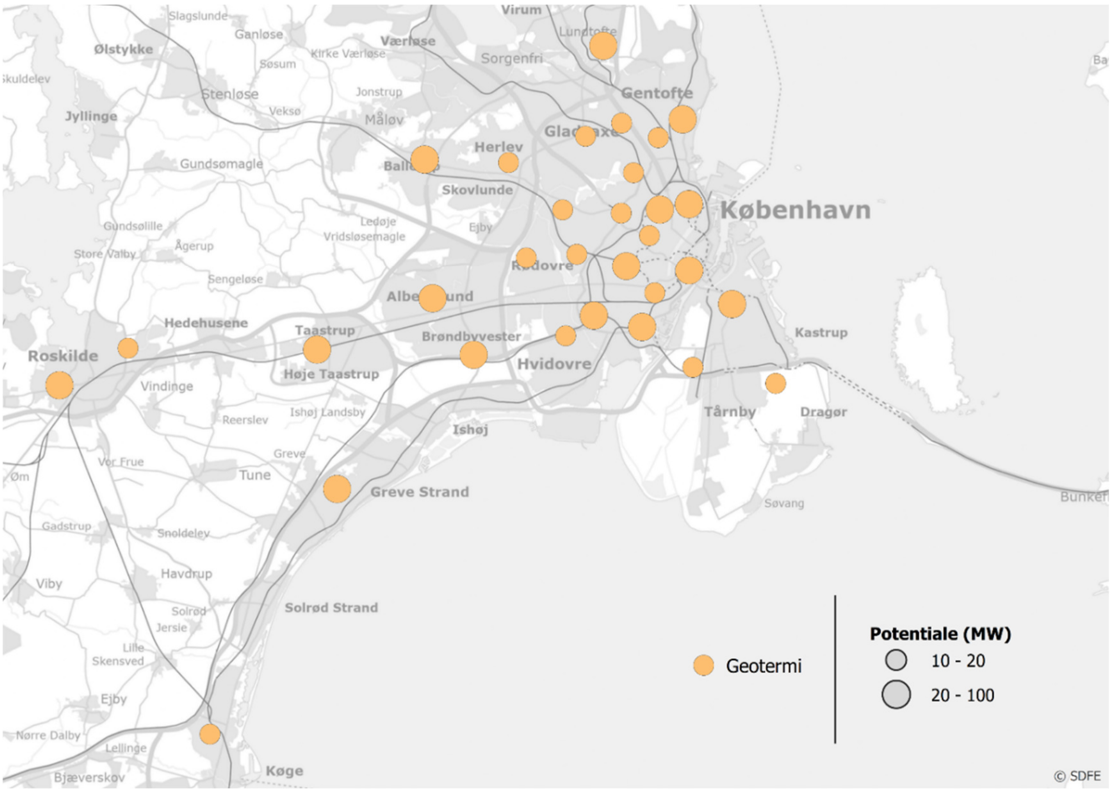

Figure 9: Possible geothermal sites and potential in Greater Copenhagen area

Seawater and geothermal energy clearly represent the greatest potential for heat pumps in the capital area, just as surplus heat from CCS and PTX can also prove to contribute a significant share in the long term.

In addition, there are a number of other heat sources, such as groundwater, air, wastewater and excess heat from industry etc. which can also make sense to use in larger heat pumps, but in more specific and limited areas.

5.5.2 Areas / location options:

To be able to realize the large heat pumps, it is important that there is also space for them, and work must therefore be done with screening areas for heat pumps and reservation of plots to the extent possible.

This involves close dialogue with municipalities and developers about urban planning and, not least, a shared understanding that the sale of land, also in dense urban areas, is a prerequisite for the roll-out of large heat pumps.

In this context, it is relevant to substantiate the designation of areas with business cases for the available heat sources, to ensure that it is the most viable projects/locations that are worked on. If several locations are at stake, business cases can also contribute to urban and heating planning with a priority order.

5.5.3 Heat pump technology and market

The market for heat pumps, including compressors for the various types of heat sources, refrigerants and their derived environmental effects for scaling up to very large plants is still in a development and demonstration phase, although in the past few years' decisions have been made on a few very large seawater heat pumps, e.g., 50 MW in Esbjerg and 20 MW in Copenhagen, but they have not yet been built.

Therefore, it is relevant for the district heating industry and other companies that work to establish heat pumps, that a close dialogue and knowledge sharing continues, e.g., via the Heat Pump Forum under Dansk Fjernvarme and with the suppliers on the market via network meetings, workshops, and tenders for projects. By using each other's knowledge and experience, it will be possible to demand more standardized and effective solutions. There is also relevant experience to be gained from foreign district heating companies, particularly in Scandinavia, which have district heating systems that resemble the Danish ones.

5.5.4 Integration in the district heating system:

Lowering the temperatures in the district heating networks – both in the flow and in the return flow – can be a prerequisite, both technically and financially, to realize the full heat pump potential in the capital area, and it can be a big challenge to lower the temperatures in urban areas with many old and protected buildings and hydraulic constraints in the network. These conditions mean that the district heating system in the capital area generally operates with higher supply temperatures than in the rest of the country. In addition, only newer heat-consumer systems are set for low-temperature district heating and conversion of consumer systems will, like lowering the temperature, require a greater effort over time.

Therefore, work is also being done to investigate whether local low-temperature networks can be established with decentralized collective heat pumps or smaller heat pumps at household or apartment block level in relation to enabling lower district heating temperatures and remedying hydraulic limitations in the network ("bottlenecks").

In addition, it is relevant to investigate the economics and possibilities of high-temperature heat pumps as a means of boosting the supply temperature in the places in the network where it is difficult to lower the current supply temperature.

5.5.5 Electricity supply and system services:

Another important area that needs to be explored is whether sufficient electricity supply and security of electricity supply can be provided in the locations where the large heat pump systems are thought to be located, and here there will be a need for a close dialogue with the local electricity companies, e.g., Radius and Energinet.

Large collective heat pumps can to a certain extent deliver system services to the electricity grid, which can improve the economics of the individual projects and it is therefore also important to have this potential analyzed and quantified.

5.5.6 Business models and framework conditions:

Overall, there is a need to prepare new business models and business cases for the different sizes and types of heat pumps and selected heat source(s).

Furthermore, it is important for the district heating industry to work to improve the framework conditions for geothermal energy, as a heat source for large heat pumps, e.g., via a support scheme, as a positive business case for the concept. Added to this is the risk, both in terms of investment and operation, which makes it impossible for the district heating companies to enter.

Here, the recent example from Aarhus, where the Maersk-owned company Innargi steps in and takes the risk in return for a fixed heat settlement price with Affald Varme Aarhus (Kredsløb), can go a long way and pave the way for future geothermal projects with large heat pumps in Denmark.

Furthermore, efforts must be made to ensure that the electricity supply offers favorable conditions (payment etc.) and technical conditions for the connection of large collective heat pumps as well as cost-effective and transparent electricity tariffs to ensure the heat pumps' competitiveness in relation to other technologies. It can, among other things, be done via the trade organizations Dansk Fjernvarme and Green Power Denmark.

6. Utilisation of project results

The results from the test program are relevant to several actors within the DH and cooling sectors, including DH companies, manufacturers, service companies and Academia. The results regarding the potential for optimizing COP gives a clear indication on what to focus on in future projects. With the recent unstable development in the power prices combined with the challenges in the years to come regarding integration of fluctuating energy from wind and solar power, COP will continue to play a very important role for the implementation of large-scale HPs in terms of cost efficiency and resource optimization (reducing power consumption).

The PhD study conducted within the SVAF project has developed a number of models and tools that have contributed to the project by qualifying the design and the setup of measurement points delivering data to the test program as well as more general considerations regarding the optimization potential of HP technology for DH purposes.

Furthermore, the results from the test program coincide with the results from the steady state model of the SVAF HP regarding a low COP improvement potential related to adjusting compressor settings. This indicates the benefits of using steady-state cycle models for optimizing HP design and operation, and that it could be relevant to explore this approach further.

The Model also confirmed that the two-stage compressor design chosen by the partnership was optimal in terms of COP. Due to insufficient operational data, these model results have not been validated, but so far COP has been satisfactory when the HP plant has been up and running and the concept is widely used in HP tenders and realized projects today.

HP suppliers are generally challenged with time and money spent on delivery of HP concepts for the business case development of potential customers. Therefore, the project aimed to assist on this, by DTU developing a design tool as part of the PhD study that could suggest the design with the most optimal COP depending on local system parameters. The tool was named HP config[7] and more details are presented in appendix 4.

An important result from the project is among others detailed numerical models of the SVAF heat pump system as well as other ammonia system configurations. These models are the basis for several publications and have been used as the core of the decision support software tool HP config, which is made available for heat pump customers and designers for system analysis and optimization.

In addition, several other numerical models for cycle analysis, component analysis and analysis of heat pumps into the energy system have been developed. These models are available for future research and are documented in reports, articles, and theses.

The results of the projects are included as part of the master's level course Energy Systems – Analysis, Design and Optimization at DTU as an example of how the theory in the course may be applied in practical applications.

7. Project conclusion and perspective

Since the project started out, there has been an intensive development within the implementation of largescale HPs for DH purposes. When the electricity tax was reduced for introducing more renewable energy sources the business case for large scale HPs improved drastically. In DH areas with natural gas the incentive to build larger HPs has been further increased by the phasing out of subsidies for DH based on natural gas. Another important development to point out is that HP suppliers have worked hard to meet market demands and have upscaled their products and to some extent larger units have become off the shelf technology. These developments have supported a large increase in realization of HPs in DH areas all over Denmark.

7.1 Main results from test program:

Potential for optimisation COP performance by adjusting compressor settings is estimated to be less than 5%. Thus, in terms of COP it is more relevant to focus on optimising the HP integration with the heat source as well as the integration with the DH system. It is not new that sink -and source flow and temperatures have a big impact on COP, however the potential of optimising the compressor system itself has been unexplored in practice until now.

7.1.1 Results and uncertainty:

The test programme has been challenged regarding establishing a stable data reference for the tests, but it is still viewed as a valid conclusion that COP optimising potential by adjusting compressor set points is limited.

[7] file://MEK-403-007-05P/Users/brel/OneDrive%20-%20Danmarks%20Tekniske%20Universitet/hpconfig/HP%20config.7z

However, the test has mainly focused on isolated adjustments, so combining adjustments of several set points has not been tested. The EUDP project Digital Twin for large scale heat pumps (Case no. 64019-0570) lead by TI aims to among other to investigate this potential further.

7.1.2 Recommendations for an optimal operation strategy

Below a number of recommendations for an operational strategy are listed based on the short-term test program by TI and the experience gained from HOFORs operational staff.

Where the focus of the test program was COP optimization and overall goal of the project was also to obtain operational stability with the chosen heat sources – both topics are addresses in the following.

- Synchronization of load and pressure for HP1 and HP2 causes a marginal increase in COP and perhaps more importantly ensures more stable compressor operation in order to avoid too much stress of the compressors.
- A lower level of refrigerant in the separator increases COP marginally but apart from this also enables a smaller refrigerant filling which is an advantage in terms of risk and safety.
- Regarding sea water specifically: A lower cleansing frequency for the sea water filter ensures a more stable flow for the heat exchanger system, which provides benefits both in terms of COP an more stable operation
- Regarding sewage water specifically: Less cleaning in Place operations is required than was the case in the first months of operation as long as the sewage water flow is kept stable. However, this can mean prioritizing stable operation over COP, if the CIP procedure is postponed. An optimal CIP frequency is still relevant to investigate further in the heat seasons to come.
- During the test program is has been possible to attain a forward temperature of 95 C – which was one of the goals in order to test if large scale HPs can serve as a stand-alone However, since this is obviously costly in terms of COP and power consumption, it is not expected to become a standard performance criterion during the winter season. However, this could become more relevant for a larger HP facility with a larger effect on the temperature level in the district heating network as a peak load production unit, as an alternative to electric boilers with a COP of 1, in situations with high electricity prices

Based on operational experience: a slightly different CIP strategy is used for sewage and seawater respectively. For both heat sources the acid-based product from the heat exchanger supplier is applied, but in the case of sewage water lye is used before the supplier product in order to remove grease from the heat exchange.

7.1.3 Results regarding HP autotune and HP doctor:

Regarding the HP autotune it is concluded that this type of machine learning function is less relevant due to the relatively low potential for compressor optimisation mentioned above. As for the HP doctor and data optimised maintenance more data and operation experience are required for forming final conclusions than has been possible to generate due to project delays.

After the SVAF project has been completed TI is still interested in following performance data of the SVAF HP over the next year to access the further potential for the HP doctor in context of the Digital Twin project.

It will be very important for the project partners to follow up on the development and results of the HP Doctor activities as these will be very relevant for future large heat pumps in the district heating system.

7.2 Perspectives:

Although many HP projects have been realised and many more are underway, several of these projects are "firsts" when it comes to scale, choice of technology and or choice of heat source i.e. many are looking forward to the results from the startup operation of the large scale HP in Esbjerg (50 MW) which will be the largest HP based on seawater in Denmark, the largest HP using CO2 as refrigerant in combination with turbo compressors. In other words, there is still an urgent need for knowledge sharing regarding improved design and heat source integration going forward with implementing large HPs for DH in Denmark and other countries with DH systems.

With the uncertainty regarding the development of electricity prices and the expended tendency for large price variations, COP remains a very important issue, when developing and implementing HP technology.

Learnings from development of the SVAF test program by TI – appendix 2

TI has a lot of experience regarding tests of HPs for heating purposes on a smaller scale in a controlled environment and has only in recent years started testing industrial scale HPs on site. Therefore, it was necessary for TI to develop a concept and a manual for the SVAF test program in cooperation with DTU among other project partners. TI estimates that the test concept and the manual in particular can be used as inspiration for testing new types of HP concepts regarding COP optimization potential – both in terms of adjusting compressor settings but also in terms of optimizing i.e., the operation of the heat exchanger system. The approach applied in the test manual (cf. Appendix 3) could be relevant to suppliers and FAT tests as well as for expanded SAT test to plan for the most optimal operational strategy for a specific HP facility in terms of COP and other operational benefits such as what the different heat exchangers contribute with in terms of increasing COP which can be used to decide if they should be installed or not.

During the design process of the SVAF HP it was decided to perform the datalogging on a per second basis in order to investigate the dynamic respond of the system to changes in parameters, meaning the fluctuation of the system while adjusting to new parameters. However, the limited hours of testing the HP Doctor have not allowed for any final conclusions. The detailed level of data could give indications on further ways of optimizing COP and other operational benefits such as using drop in suction temperature along with dropping efficiency of the evaporators to indicate freezing of the plate heat exchangers and react to this by increasing the suction temperature and eliminate the freezing risk.

As mentioned SVAF has been cooperating with the EUDP project Digital Twin, where SVAF data will be studied for further dynamic effects pointing towards potential operation optimization.

Results from DTU research – appendix 4

The results from the research contribution of the modelling and simulation analyses developed during the project by DTU in cooperation with TI are primarily based on the large models of ammonia heat pumps developed for several cycle configurations. These models have been applied in several studies published in international scientific conferences and journals as well as in student theses. The models are directly available for further use in the HP Config software that can be applied by heat pump end users and system designers for decision making based on energy efficiency and economic assessment. In addition, the models have been applied in several studies that document the options for improved control of the SVAF heat pump, the benefit of efficiency improvement methods, a mapping of the most promising configurations for the relevant range of temperature profiles, and the application of the principles of pinch analysis in the configuration of complex heat exchanger networks in heat pumps. Furthermore, other modelling analysis have focused on comparison of ammonia to other refrigerants and on the flexible operation of the heat pump for integration into the energy system by regulating power.

8. Appendix

- Appendix 1: SAT test report
- Appendix 2: Analysis test report, TI
- Appendix 3: Test program and manual, TI
- Appendix 4: Research contribution, DTU
- Appendix report Energy potential for large HPs in greater Copenhagen https://www.hofor.dk/wp-content/uploads/2021/01/Kortlaegning-af-effektpotentiale-for-store-varmepumper_EUDP-efteraar-2020_endelig.pdf
- Appendix report: Upscaling study for large HPs https://www.hofor.dk/wp-content/uploads/2022/08/SVAF-ppskaleringsanalyse-250422.pdf