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Final report

Experimental development of electric heat pumps in the Greater Copenhagen DH system - Phase 1

(Store Varmepumper til Fjernvarme, SVAF fase 1)

1.1 Project details

Project title	Experimental development of electric heat pumps in the Greater Copenhagen DH system - Phase 1
Project identification (program abbrev. and file)	Journal nr.: 64014-0127
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	HOFOR, Ørestad Boulevard 35, 2300 København S.
Project partners	HOFOR, CTR, VEKS, Innoterm, Alfa Laval, DME, TI, DTU.
CVR (central business register)	HOFOR Fjernvarme P/S CVR no. 26 08 92 63
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1.2 Short Description of Project Objective and Results

(English and Danish)

The aim of the project is to accelerate the use of large electric heat pumps (HPs) for district heating (DH) through industrial cooperation, research and experimental development. The project is the first phase of an expected large scale HP demonstration project and concerns development of technology concepts and test programs for two large-scale HPs with the purpose of demonstrating optimal design, SMART system integration, cost efficiency and maximal climate benefit. The results have been documented in various briefs, including findings concerning: Design criteria, choice of technology and preliminary principle diagrams along with drafts of the connections to heat and power network, building etc. The main findings are summarised in this report.

Formålet med projektet er, at accelerere anvendelsen af store eldrevne varmepumper (VP) i fjernvarmesystemet (FV) gennem industrielt samarbejde, forskning og eksperimentel udvikling. Projektet omfatter første fase af et demonstrationsprojekt, som har haft fokus på udvikling af teknologikoncepter og testprogrammer for to storskala varmepumper med henblik på demonstration af optimalt design, SMART systemintegration, kosteffektivitet og klimafordele. Resultaterne er blevet dokumenteret i en række notater, som omhandler: Designkriterier, teknologivalg, samt udkast til principdiagrammer samt tilslutninger til el-og fjernvarmenet, bygning mv. Hovedresultaterne er opsummeret i denne rapport.

1.3 Executive Summary

The project is the first phase of an expected large scale HP demonstration project and concerns development of technology concepts and test programs for two large-scale HPs with the purpose of demonstrating optimal design, SMART system integration, cost efficiency and maximal climate benefits.

The focus has been on testing heat sources with sufficient energy potential for supplying the Greater Copenhagen Area (GCA) DH network. One HP facility will be based on Geothermal Energy and situated at Amager Heat and Power plant. The other HP facility will test low temperature heat sources: Sea water and sewage water and will be situated at Sjællandsbroen sewage pumping station.

The results of the project will be used as the foundation for the second phase concerning the detailed design and construction of the two demo- HPs followed by the implementation of the test program. An EUDP application was submitted in September 2015 concerning phase 2 and funding has been granted on specified conditions.

For the HP facility based on geothermal energy the following design concept has been found relevant: a two-stage Hybrid HP concept using traditional pressure stage ammonia compressors. A hybrid HP uses a refrigerant mixture of ammonia and water, providing a lower boiling point and is therefore able to operate with low pressures and better energy efficiency due to lower differential pressures when delivering high outlet temperatures.

For the HP facility based on sea and sewage water a concept with two units connected in series has been chosen each designed as two-stage ammonia refrigeration systems for optimal COP performance. As low winter sea water temperatures require cooling close to 0°C, a hybrid HP is not a suitable solution because it cannot be operated due to risk of freezing of the water in the refrigerant circuit.

A two-stage ammonia refrigeration system will provide more demonstration value due to the pressure required for the ammonia compressor to achieve the maximum DH supply temperature (90 °C). It will test the limits of the technology and thereby provide important knowledge as to whether ammonia compressors are suitable for these high temperature requirements of larger DH systems.

The test programs will focus on the parameters most important to maturing HP technology: Optimising COP (Cost efficiency) and testing SMART system integration (high supply temperatures for DH and regulation flexibility towards the power market). In addition, the largest possible components will be tested in order to explore the potential for upscaling to large-scale facilities (50-100 MW). _However, the scale of the prototypes, i.e. 5 MW, will also be relevant, both in outer regions of GCA and in Denmark's large number of decentralised DH areas.

For the geothermal HP the specific test areas are: Optimised geothermal well performance with lower return temperatures. The increase of performance and stability of supply from the well is crucial to improving investments in geothermal energy. For the sea and sewage HP the specific test areas are: Development of a CIP strategy to prevent fouling and optimise COP in a cost efficient way.

The results from the test programs will provide an extensive data material relevant to DH companies and the HP sector in terms of demonstration and maturing the technology.

The business case (NPV calculations) comes out negative for the demonstration HP facilities. This is due to high investment costs combined with maintenance costs expected to be higher than the reference production technology in the GCA: Biomass CHP (wood chips). The higher maintenance costs are caused by both tax regulations on power as well as technical issues with heat sources and potential for optimisation of O&M costs.

In the GCA, heat production units are prioritised - given operation time, according to their variable O&M costs. It is therefore essential to optimise COP and O&M costs for HPs to become viable. HP technology is already economically relevant for decentralised DH areas, where the reference technology is gas boilers – assuming there are no technical issues with the available heat sources. The Danish Energy Board is not expecting HP technology to become competitive in central DH areas before 2030 (Danish Energy Board, 2013). In the GCA this will happen gradually with the phasing out of the existing CHP plants and the anticipated revision of energy tax regulations. However, in order for the large electric HPs to be ready for implementation, the technical issues concerning heat sources with adequate energy potential and the optimisation of design and operation costs have to be in place in due time. Finally, an important part of preparing for future HP investments is the reservation of relevant HP building sites with proximity to heat sources, DH net and power grid. Plots for technical facilities are scarce in larger cities and site specific costs can be high. In the current project costs related to additional equipment affected by site specific factors make up app. 60% of the investment.

1.4 Project Objectives

The objectives of phase I, concerning analysis and design, are to deliver technical concepts for two 5 MW heat pumps for DH purposes with high technical (COP) and economical efficiency relevant for up-scaling based on:

- Geothermal energy (located at existing well at Amager Power Station owned by HOFOR.)
- Sea water and waste water (located at Sjællandsbroens sewage pumping station owned by HOFOR).

In addition, the objective has been to develop a suitable test program for each heat pump, in order to provide the required knowledge and experience for accelerating the use of large-scale HPs for DH purposes.

The risks associated with delivering these results have been: 1. Lack of data from HP producers, due to unwillingness to spend time and resources on requests from potential customers without a sales contract. The HP market for DH is undeveloped and HP producers generally prioritise the more developed cooling market 2. Other projects and customers are competing for the time and resources of the commercial participants. However, despite delays of specific deliverables along the way, it has been possible to meet the project' s overall deadline and to fulfil the milestones agreed upon, regarding development of relevant design basis principles, technical concepts and test programs, which will serve as the foundation of phase II concerning detailed design, construction and demonstration.

1.5 Project Results and Dissemination of Results

In this section the results will be presented regarding the design criteria (also referred to as the design basis), the development of the technical design concepts and the outlay of a test program for each HP technology respectively.

The design basis has been developed based on two general criteria: Optimal COP (Coefficient Of Performance), cost efficiency and system integration in accordance with the heat and power markets.

1.5.1. Design Basis for the Heat Pump Facilities

The design basis includes the design criteria on which the technical design concepts and later on the detailed design of the HP facilities will be based. This also includes drafts for the support facilities, including the building, the connections to the heat and power network, and the heat sources. Since these are not in themselves part of the innovative development, they are not presented as part of the main findings and can be found in appendix reports.

The key design criteria concerning the two HP facilities, as the main focus of the project, have been: choice of refrigerant, the scale of the test facility, the supply temperature to the DH network and flexibility in regulation which are the same for both heat pumps, whereas for the technical data of the local DH network and the existing geothermal well: mainly temperature levels and differential pressures, are specified separately.

1.5.1.1. Choice of Refrigerant and Compressor Technology

The natural refrigerant Ammonia (NH_3) has been chosen due to its highly energy efficient features and because it is industrial standard. Unlike i.e. the refrigerant CO_2, NH_3 compressors are available in relatively large sizes compared to other natural refrigerants. Finally, NH_3 as a natural refrigerant is in accordance with Danish legislation, which bans synthetic refrigerants above 10 kg system filling charge. The downside is that ammonia requires high pressure compressors, pressure vessels and heat exchangers. The higher the DH supply temperature, the higher pressure is required, leading to various challenges such as a limited availability of high pressure refrigeration components, higher degree of wear and tear on critical components with typical half as long service intervals as under normal conditions. During the test and following operating period, the additional maintenance requirements shall be monitored and registered for a better and full validation of the exact O&M costs in relation to operating hours, start/stops, operating conditions and refrigeration technology.

The scale of the test facility is 5 MW heat capacity, which is based on the intention of testing the large, commercial ammonia (NH3) HP components available in order to analyse potentials and barriers to up-scaling HP facilities to around 50 MW to 100 MW heat capacity. The refrigeration components have to be commercial available because testing a 5 MW HP facility already poses a considerable challenge due to several factors: 1. Limited availability of large compressors for natural refrigerants compared to large scale machines operating with synthetic refrigerants. 2. Few experiences from test facilities above 1 MW-2 MW using natural refrigerants combined with the performance requirements for the Greater Copenhagen DH system both in terms of COP and supply temperature. Furthermore, up-scaled, custom made components would be much more expensive and one of the challenges of maturing HP technology is to keep investment cost at a reasonable level, while testing the performance of the technology for DH purposes, before taking it to the next level.

Compressor sizes are compared by a value called theoretical swept volume (theoretical gas displacement). Industrial refrigeration compressors are most commonly twin rotor oil injected screw or reciprocating (piston) compressors. Screw compressors have few moving parts and therefore less wear parts compared to reciprocating compressors and have longer service intervals. Screw compressors are manufactured in sizes with many times bigger swept volume than reciprocating compressors and can in general operate with a higher differential pressure i.e. higher temperature lift form source to sink. Consequently screw compressors have been chosen for this project, as they are better suited for larger industrial applications – technically as well as economically.

The table below shows the largest available high-pressure compressors for industrial refrigeration purposes.

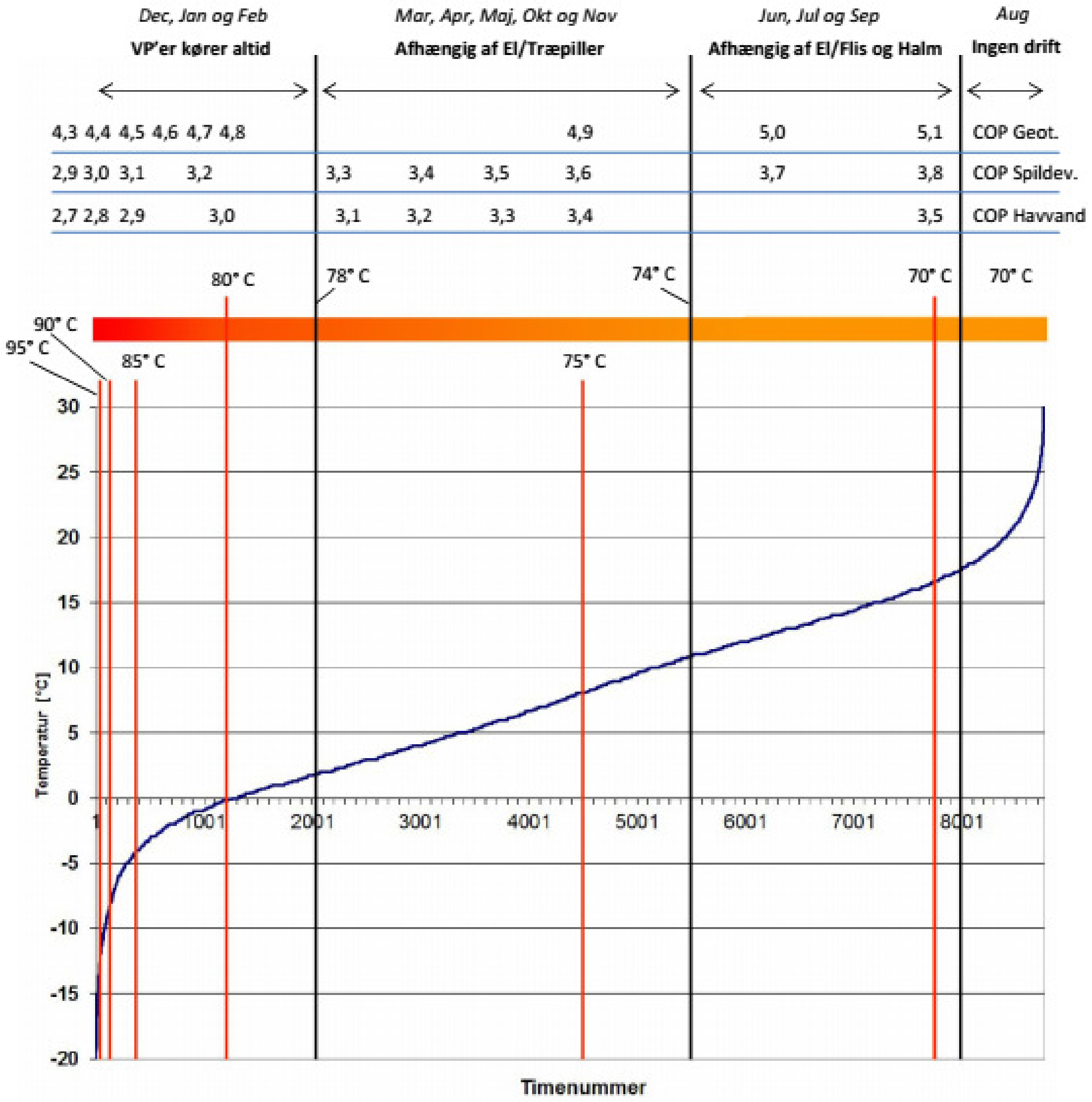
Largest HP model R717 compressors from various industrial refrigeration manufactures						
Producer	Compressor type	Size (teoretical swept vol.)	Max. discharge pressure	Approx. Max. sink outlet temp.	Approx. Heating capacity	Note
		[m3/h]	[bar]	[°C]	kW @ Te/Tc [°C]	
Sabroe (JCI)	recip	452	40	70 -72	1.300 @ 35/72	
Sabroe (JCI)	recip	250	60	90	650 @ 35/90	
Sabroe (JCI)	screw	1.800	42	70-72	5.150 @ 35/72	$T_{evap.}$ must be < 15°C
Sabroe (JCI)	screw	596	52	88-90	1.600 @ 35/90	
GEA	recip	202	52	80-82	530 @ 35/82	
GEA	screw	4.150	52	80-82	12.265 @ 35/80	
GEA	screw	1.740	63	90-92	4.670 @ 35/90	N/A at this time or on request
Mayekawa (Mycom)	recip	602	60	88-90	1.435 @ 35/90	
Mayekawa (Mycom)	screw	3910	60	90-92	9.669 @ 35/90	Cast steel
Vilter	mono screw	863	63	90	2.490 @ 35/70	Ductile iron
Vilter	mono screw	x	76	100-105	x x	Cast steel
Howden	screw	815	40-45	70-75	1.850 @ 35/75	Not active in heat pump applications
Howden	screw	x	75	x	x x	API619 design for gas compression
Snowkey	screw	4.280	63	90-92	12.650 @ 35/80	Unknown make from China

1.5.1.2. SMART System Integration

In terms of system integration of heat pumps with the DH system in the Greater Copenhagen Area (GCA) the supply temperature (also termed sink outlet temperature) is very important. In wintertime the required temperature can be up to around 95°C -100°C. These temperature levels are required in a DH network the size of the GCA, in order to transport heat over long distances, and also in order to supply a number of old, protected buildings unsuitable for energy renovation in the center of Copenhagen. Furthermore, a significantly lower *maximum* winter supply temperature of around 70°C -75°C, would require new heating installations in the form of radiators dimensioned for lower temperatures in the vast majority of buildings. Yet, throughout most of the heating season 80°C is sufficient.

The higher the required outlet temperature the more electric energy is required to lift the input temperature from the heat source, leading to a reduction in COP.

Therefore, the supply temperature and especially the required temperature in the future DH system have been discussed extensively in the project. The diagram below illustrates the coherence between the outside temperature (y-axis) and the required DH supply temperature in relation to the number of DH operation hours a year (x-axis). Above the diagram the COP of HPs based on geothermal energy, sewage and sea water respectively have been calculated based on the level of the supply DH temperature (COP is only related to the HP itself).



Reference: Teknologisk Institut, 2014.

There is a continuous effort to optimise and to lower the supply temperature in the DH distribution net (a reduction of around 1 °C per year in Copenhagen City) e.g. through general optimisation and initiatives such as renovating buildings/heating installation and low temperature DH areas, However, this is not enough to counter the requirement of high temperatures as a means of transporting energy over long distance or ensuring security of supply for the old town area. If HPs are be placed as decentralised production units in DH sections within the GCA, where lower supply temperatures are required locally, this means that other units in the GCA system will have to provide the higher temperature heat in order to maintain the temperatures required for the DH network.

The final decision of applying 80°C, as the optimum design point for both HPs, has been weighed between criteria of security of supply and cost efficiency. Thus the average supply temperature requirement in the DH system is expected to be app. 80°C, for many years to come and when applying a hybrid HP (refrigerant: NH_3 and H_2O cf. Technical design concepts in 1.5.1.) the COP will still be reasonable with a high supply temperature and also capable of testing a supply temperature of up to 95°C.

Regarding system integration with the power market, dynamic regulation addressing the spot market is the main aim. This is relevant in situations where operation is either not economically viable due to high power prices caused by e.g. reduction in wind power generation or in the reversed situation where the heat pumps should start up if there is a sudden drop in power prices.

Start up and stop response will be timed to evaluate if larger HPs can have relevance to other power markets as well with higher demands on response times. However, it should be taken into consideration that frequent start up and stop sequences affect both the efficiency and the life span of mechanical and electrical equipment.

1.5. 2. Technical Concepts for the Heat Pump Facilities

During the analysis and design phase (phase 1) of the project, several design solutions have been discussed, both with regard to how to connect the HP’s heat source side into the existing geothermal installation, how and where to connect and implement the HP’s sink side to the existing DH system, and how to design the ammonia refrigeration system in order to obtain the highest possible COP and operational flexibility. Since the development of the HP configuration has been the main innovative endeavour of the project, this will be the focus in this presentation of the technical concepts, as buildings, pipes etc. are only support facilities and will be constructed according to usual standards. However, because investment costs are a barrier for the deployment of large HPs using natural refrigerants, savings opportunities, that have not been decided on in phase 1 will be reviewed and included in the final contract if not in contradiction with the demonstration-objectives in phase 2. The technical design and PIDs are described further in the appendix reports, which can be acquired upon request.

1.5.2.1. HP Integration with Source Cooling and Sink Heating in Multiple Steps

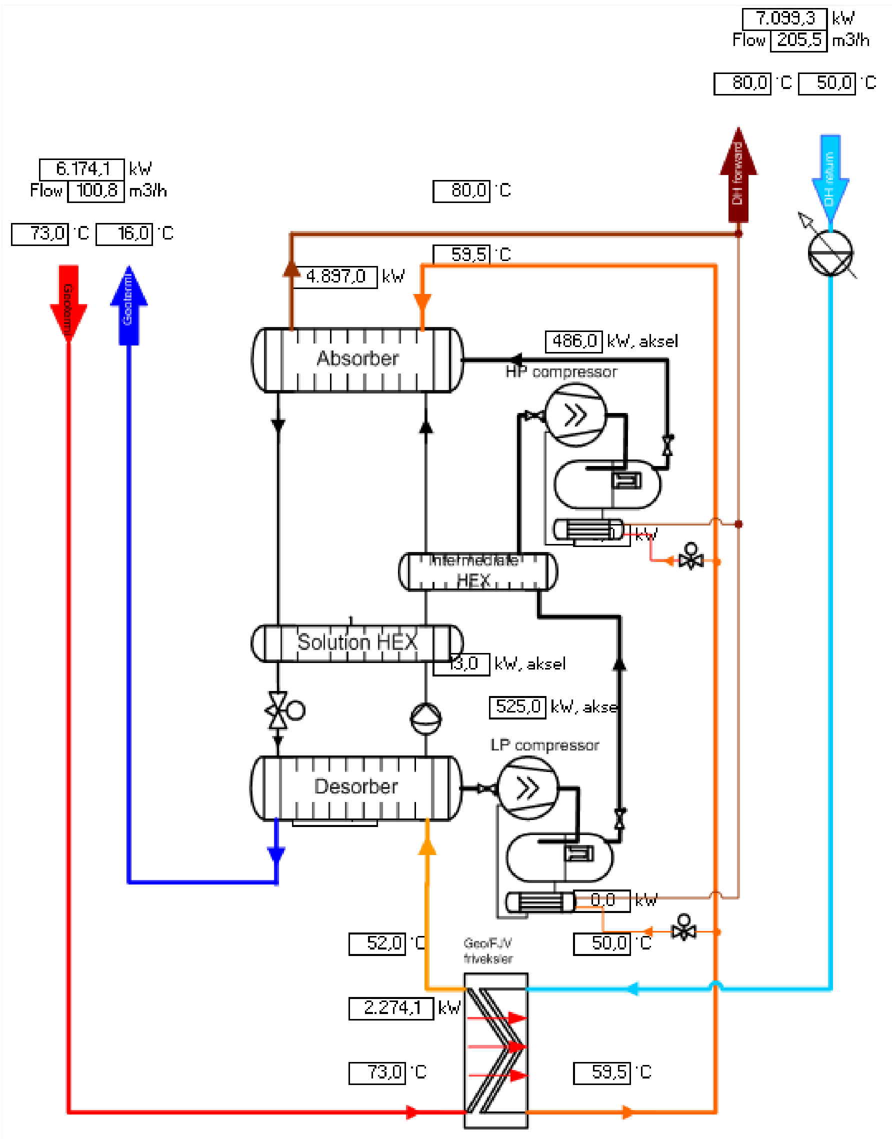
The use of cooling and heating in multiple steps by two HPs within each HP facility has be considered and found optimal in order to achieve the optimal COP. When connecting the HPs in series for cooling and heating in multiple steps, the HP's are mutually dependant and the control system and philosophy shall be able to determine the optimum balance between the HPs with regard to in/outlet temperatures and corresponding capacity control.
The pros and cons of cooling the source and lifting the temperature of the DH water in two steps have been deliberated extensively and has been analysed by DTU (cf. Technical note appendix 3).

1.5.2.2. Technical Concept for the Geothermal HP

For the geothermal heat pump facility, a two-stage Hybrid concept has been chosen using traditional pressure stage ammonia compressors. A hybrid HP uses a refrigerant mixture of ammonia and water, providing a lower boiling point temperature and is therefore able to operate with low pressures and better energy efficiency due to lower differential pressures when delivering high outlet temperatures. The Hybrid technology also has its advantages and high COP values in applications with a high source in/outlet temperature differences as well as high sink temperature differences providing an efficient temperature glide in the refrigerant mixture, which boost the absorption and desorption energy exchange in the system.

As the geothermal heat source temperature is higher than the DH return temperature the first step cooling of the geothermal water and heating of the DH water is carried out in a water/water heat exchanger. With the design basis temperature set approx. 2.2 MW heat is transferred in this heat exchanger.

The two-stage hybrid HP system has been designed and connected as per below principal flow diagram.



Performance data @ DH = 80°C:

- Cooling capacity: 6,174 kW
- Heating capacity: 7,099 kW (Absorber 5 MW, heat exchanger 2 MW)
- Power consumption: 1,123 kW (incl. losses in motors and frequency converters)
- Heat Pump COP: 4,3
- Overall $COP_{heating}$ brutto is 6.3
-

Performance data @ DH = 95°C:

- Cooling capacity: 5,189 kW
- Heating capacity: 6,072 kW
- Power consumption: 1,058 kW (incl. losses in motors and frequency converters)
- Overall $COP_{heating}$ brutto is 5,7

The maximum DH temperature expected with hybrid technology is up to 110°C, in this case designed for up to 95°C. As the pressures with the Hybrid design are below traditional design pressures, there is no dependency on a specific compressor manufacturer.

The geothermal and DH water piping systems are simpler and independent as there is no intermediate circuit with a fixed temperature from the geo/DH heat exchanger.

To sum up, a hybrid technology solution has the following advantages compared to a traditional NH_3 compression HP solution:

- At a DH water temperature of 80°C, the COP of the Hybrid HP is approx. 13 % higher
- Hybrid HP implementation with the geothermal/DH heat exchanger is simpler as there are no fixed intermediate circuit temperature to be achieved as required with a system design with two separate HP's
- Hybrid HP uses low pressure components hence more flexibility in choice of compressor manufacturer and types and hence larger components for up scaling are also more easily available.
- Lower pressure means less wear and tear of the components.
- The Hybrid HP can produce higher DH water temperatures

Thus a hybrid HP is considered as the best choice even when considering the downsides:

- Hybrid HP requires more machine room height. Estimated 6 metres at an area of approx. 3 x 4 meters.
- Investment cost of the Hybrid HP is higher; however, due to a significant higher COP the DH production price per MWh will be more attractive.
- The hybrid technology is owned by a Norwegian company called Hybrid Energy, http://www.hybridenergy.no/en/ which presently is the only supplier of this type of systems in the market.
- The hybrid technology uses patented heat exchanger designs which may complicate and/or increase cost of the system.

1.5.2.3. Technical Concept for the Sea and Sewage HP

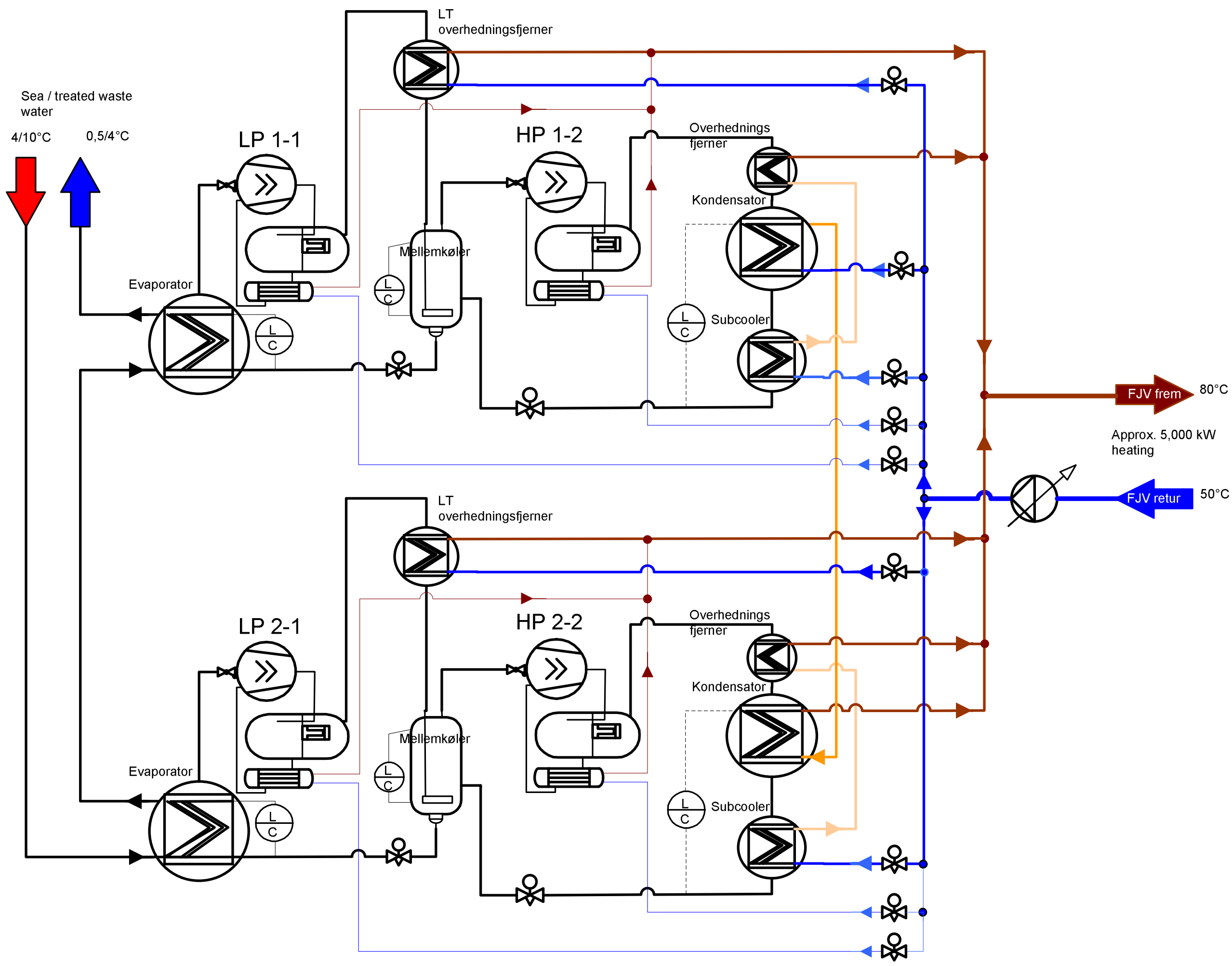
For the sea and sewage HP facility, a concept with two units connected in series has been chosen each designed as two-stage ammonia refrigeration systems for optimal COP performance.

The DH water is by this design heated to the desired DH forward temperature in two main steps enabling the facility to operate with a lower condensing temperature in HP1 than HP2 in order to achieve the maximum COP.

The HP facility will be operated and tested on one of the heat sources at a time. Thus, it is not the intention that the HP should be able to use the two heat sources in combination or to shift from one heat source to another within a short time.

The traditional ammonia HP is connected as shown in the principal sketch below.

Traditional (ammonia-R717) HP principle diagram:



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

As low winter sea water temperatures require cooling close to 0°C, a hybrid HP cannot be operated due to risk of freezing of the water in the refrigerant circuit and a low source temperature requires extraordinary large compressor sizes. A combination with a traditional compression HP design for low temperature cooling with a hybrid HP cooling the sink heat and heating to the required DH supply temperature will reduce the overall COP by approx. 14%. The reasons for the lower COP with such combination are both a low temperature in/outlet difference in the intermediate circuit between the two systems and because the two systems cannot connect by a cascade heat exchanger, thus an intermediate circuit is desired.

Secondly, this design will provide more demonstration value due to the pressure required for the ammonia compressor to achieve the maximum DH supply temperature (90 °C). Hence it will test the limits of the technology and thereby provide important knowledge as to whether ammonia HPs are suitable for these high temperature requirements of larger DH systems.

It will also be possible to some degree, to compare the operation and maintenance costs over time of hybrid technology (geothermal HP) to the traditional ammonia compression solution (sea and sewage HP). Such comparisons will have to be based on and adjusted for any differences in the way the two different facilities are operated.

Finally, it is an advantage that the traditional compression HP's normally are cheaper than the hybrid HP also when considering extra space needed in the building (including extra building height).

The main disadvantage is the high refrigerant pressures in order to achieve 90°C DH temperature will lead to more wear and tear, which can shorten the service intervals of the compressors. Typically a traditional screw compressor requires a major overhaul at approx. 50,000 operating hours. Such service intervals are reduced to half or recommended by the manufacturer to be approx. 25,000 hours if the HP is operating at 90°C or more. This project shall determine the impact of the high operating pressures.

1.5.4. Test Programs for the HP Facilities

An important result of the project is the test program developed for each of the HP facilities. These programs will dictate how the facilities should be operated during the test period in order to gain the knowledge and experience required for the further development of large scale, cost efficient HPs for DH purposes.

1.5.4. 1 General Test Program relevant to both HPs

The overall aim of the test program is to develop an operational strategy that ensures optimal performance in terms of COP and SMART system integration (DH supply temperature and flexibility in regulation towards the power market) under varying conditions.

For both HPs, the following general tests will be performed:

- Energy efficiency (COP): Test of energy efficiency of design and off-design conditions operation.

- Optimal O&M strategy: Development of a tool that can indicate the right time for components to be serviced to prevent premature or delayed replacements leading to higher maintenance costs.

- Optimal operational strategy: Taking all the test areas above into consideration.

- Development of a road map for upscaling: Focus on using the largest commercially available components and on learning points regarding optimisation of design and operation strategies that can be transferred to large-scale facilities (50 MW-100 MW). The project cannot entirely eliminate upscaling risks, but many important lessons can be extracted from the test of 5 MW facilities, especially regarding how to deal with specific heat source issues and COP, e.g. by use of design and operation optimisation tools, which can be critical regarding operation costs and feasibility.

The table below provides an overview of the test areas for the two HPs.

Test areas	Remarks	Geothermal demo HP	Sea- and sewage water demo HP
Heat source applicability **(Heat source specific issues)**	Assessment of well performance Heat exchanger concept to address sewage fouling and sea water freezing	X	 X
Energy efficiency (COP)	Test of energy efficiency of design and operational strategy	X	X
Power market integration	Geothermal wells will clog if frequent start/stop operation. Partial load will be analysed and tested.	(X)	X
Optimised O&M strategy	Development of tool	X	X
Perspectives for up scaling	Focus on largest available components	X	X
Optimal operational strategy	Taking all the test areas above into consideration	X	X

1.5.4.1. Test program specific to the Geothermal HP

Heat source applicability: The steam driven absorption HP, presently in operation at Amager Heat and Power station, has had a number of operational issues, leading to less cooling of the geothermal water and higher return temperatures for the injection well. Moreover, the effect of the return temperature on the well is not fully known. It is therefore relevant to compare the electric driven HP with the steam driven HP in terms of how efficient the geothermal well is exploited (how efficient the water is cooled down). Furthermore, it is relevant to monitor the conditions of the injection well to investigate the influence of the return temperature on precipitation of substances such as calcium from the geothermal water leading to clogging of the well.

SMART system integration: Another factor affecting the geothermal wells is frequent start/stop operation, which tends to clog up the wells. Therefore, geothermal HPs are generally, or just due to geological conditions in GCA, not well suited for SMART operation/regulation according to the price signals or the stability needs of the power market. Yet partial load operation will be tested because it will be relevant for situations with very high power prices, and in the summer, when heat consumption is low and mostly covered by heat production from prioritised waste incineration.

1.5.4.2. Test Program Specific to the Sea and Sewage Water HP

Heat source applicability: The main challenge of using treated sewage water as heat source is fouling of the heat exchanger, which derives from bacteria still present in treated sewage water. The bacterial growth leads to a biofilm coating on the surface of the heat exchanger, reducing heat transfer capacity and thereby the overall efficiency of the HP system. For some applications, this issue has been solved by means of a shell and tube heat exchanger, where constant mechanical cleaning in a closed loop prevents fouling from taking place (HOFOR, 2013). Yet shell and tube heat exchangers are generally known to require more space and provide less efficient heat transfer and a lower COP compared to plate heat exchangers. Since a high COP and low operation costs are very important in terms of commercialising large-scale HPs, it has been decided to use plate heat exchangers and to mitigate the fouling issues with this type of heat exchanger. An important area of the test program is therefore to test different CIP (cleaning in place) approaches and frequencies. Furthermore, the project shall develop a tool that monitors the development of fouling in order to initiate cleaning before heat transfer efficiency is significantly reduced.

Most HPs in Scandinavia based on sewage water as heat source uses shell and tube exchangers. The project group has visited a HP in Helsinki using plate heat exchangers. One of the main findings of the trip was that even though fouling of the heat exchangers reduces the performance and COP of the HP significantly, the operation data indicated that with a more systematic approach to CIP and flow control, plate heat exchangers could be applicable for sewage water and would very likely provide a higher COP than with a shell and tube heat exchanger system.

The energy potential of seawater is in theory an infinite heat source but there is a huge challenge regarding the low seawater temperatures in winter, where the heat consumption and the required temperatures for the DH network are highest. First of all, it creates an issue in terms of maintaining a reasonable COP when the input temperature is low. Secondly, there is an issue with preventing ice formation in the facility. There is a potential risk that when seawater drops to around 2-3 °C, the HP must be taken out of operation, because of too low COP and/or due to the risk of ice formation in the evaporators. This in itself is important to ascertain, because it will decide whether NH_3 based HPs have any potential with seawater as a heat source.

One idea has been to shift to using waste water in cold periods or to heat up the sea water with the waste water. However, this solution does not provide the scale of heat source energy needed in order to supply GCA with around 250 MW-300 MW heat capacity at HPs (since the energy potential of waste water is around 100 MW-150 MW).

Another option to deal with ice-build-up is to use HPs based on water vapour compression technology. These HPs use water as refrigerant and generate ice as part of the process. They have a high efficiency and are potentially scalable to large sizes. However, water vapour-compression technology has not been considered relevant for this project as the technology is still under development and not commercially available (Madsboell H. et al. 2015).

SMART system integration: Regarding operation and regulation according to the power market, dynamic operation addressing the spot market is the main aim. This is relevant in situations where operation is not economically viable mainly because of high power prices due to e.g. reduction in wind power generation, or in periods with low heat demand in the summer.

Start-up and stop sequences are therefore very important to test, in order to assess the flexibility of HPs in order to respond to spot market prices which are hourly based. The response time of the HP concerning the duration of operation start-up and stop will be tested as well as the long-term effect on the facility.

The test programs have been divided in a short term and long term period, described in the tables below.

Short term test areas 2017-2018	Measurement and relevance
Operational control and regulation	Relates to test if flow and temperatures can be regulated in accordance with seasonal variation in heat source temperatures and required output temperature. Both the maximum possible speed of load changes and the HP's reaction on load changes in terms of e.g. changes in COP will be analysed. The HP system's dynamic reactions will be compared to the simulation model and adjustments are made where needed. If test parameters are different from what the various models have shown, an explanation should be found and the HP system adjusted accordingly.
Performance (MW) and COP	Will be measured during various operation modes and compared to original calculations from supplier and the modelling. Deviations are investigated and actions taken. The result from the test will be used in the development of the optimal O&M strategy. A "HP doctor" will be considered to alert the operator of possible loss of efficiency or threatening system failure.
Operational range	Relates to finding the actual operating envelope in which the HP system can safely operate. This information is used to decide what actions to take by the SCADA system to recover and keep the HP system in operation/within the envelope without having shut downs.
Adjustment and optimisation of operation	Based on the operation experience/results obtained in the short-term test, the control strategy will be re-evaluated and adjusted to obtain the most optimal one.
Start and stop sequences	Related to SMART system integration with the power market, including wind power integration. Relevant regarding timely supply of the relevant temperature to the heat market as well as regulation regarding power prices, where start up and closing reaction times are important. These will be used to estimate when it is economical to use the HP in the regulating power market. The part load efficiency under start and stop of the HP will be investigated to be able to calculate the costs of start and stop.

Long term test areas (2018-2021)	Measurement criteria and relevance
Facility condition measurements and/or inspection	Relates to durability and maintenance requirements of the facility components – important in

	terms of O&M costs. Will be used to lay out an O&M strategy based on among others load history rather than time-based maintenance which will be too costly.
Geothermal well condition	Indicators will be identified and measured. Well condition is vital to ensure performance and affects O&M costs.
O&M strategy	Relevant indicators will be described as decision base for an O&M strategy. Timing is important for O&M costs. The aim is to reduce the maintenance costs and thereby reduce the production costs per MWh.
CIP (cleaning in place)	Required CIP frequency, factors affecting it and measures to reduce CIP frequency will be investigated. This is especially relevant for when using sewage as a heat source. The test of different approaches to CIP is very important regarding O&M costs.
Overall operational strategy	The strategy will be developed based on data analysis from both short and long term test results. It is one of the main results of the project relevant in terms of up scaling and with relevance to other HP projects in general.

1.5.5 Business case

Net present value (NPV) calculations, including both investment and O&M costs for the two HPs have been carried out over a 20 year period, representing the expected technical lifespan of HP technology. The results come out negative in both cases. This is due to high investment costs combined with maintenance costs expected to be higher than the reference production technology in the GCA: Biomass (wood chips) CHP. The higher maintenance costs are caused by both tax regulations on power as well as technical challenges with heat sources and optimisation of O&M costs. For the geothermal HP there is a chance of a positive NPV, but this is mainly due to the fact that the geothermal well was already in place and therefore calculated as a sunk cost.

In the GCA, heat production units are prioritised - given operation time, according to their variable O&M costs. It is therefore essential to optimise COP and O&M costs for HPs to become viable. HP technology is already economically relevant for decentralised DH areas, where the reference technology is gas boilers - assuming any technical issues regarding the local heat source have been solved. The Danish Energy Board is not expecting HP technology to become competitive in central DH areas before 2030 (The Danish Energy Board, 2013). In the GCA this will happen gradually with the phasing out of the existing CHP plants and anticipated revised energy tax regulations. However, in order for large electric HPs to be ready for implementation the technical issues concerning heat sources with adequate potential and optimisation of design and operation costs have to be in place in due time.

Regarding high investment costs (app.10 mio. Kr./MW heat capacity) one of the findings are that only around 40% of the investment costs are related to the actual HP technology, whereas the remaining 60% are related to the additional equipment required. An example is the cost for the Geothermal HP facility building, which requires pile foundations, because of the weak soil layers in the Amager area cannot sustain the weight of the building. It would be optimal to look for less expensive building site conditions, but sites for technical facilities in the GCA are scarce and have to be situated in proximity to the relevant heat sources. Proximity to the DH net and power grid are also important to keep costs down. In other words reservation of relevant plots in due time is vital to future HP investments.

1.5.6. Commercial Aspects and Dissemination of Project Results

The commercial aspects of the project will not be realised before the second phase where the demonstration of the HP technology, will be used in the sales and marketing activities of the participating partners.

The results of phase 1 have been presented to a number of stakeholders at the closing seminar of the project's phase 1, attended by: DH companies, HP contractors, consultants, Danish Energy authorities and energy sector organisations. Information (this report among other) will also be available on the websites of the partners and the EUDP.

The project has been presented at a HP theme seminar held by the Danish DH association in April 2015 and will be presented at similar events in the year to come.

The publications and press articles related to the project are listed in appendix 2.

1.6 Utilization of Project Results

The results of the project will be used as the foundation for the second phase of the project concerning the detailed design and construction of the two demo- HPs followed by the implementation of the test program. The technical concepts and deliberations of phase 1 are also relevant to the commercial partners in relation to customers with interest in HP projects aimed at DH.

The participants do not plan to take out patents as the novelty of the project lies in the design development and adaption and experimental tests rather than the innovation of new technology.

An EUDP application was submitted in September 2015 regarding the second phase. The same partners participate. However, TI has chosen to be a partner, whereas BIOFOS prefer to be part of the reference group in phase 2.

The data generated from test programs will provide the basis for a number of analyses in phase 2 regarding an optimal strategy in terms of COP and SMART system integration as well as perspectives for up scaling the technology.

Technical knowledge and economic results from the realisation of phase 2 will be used as the basis for the DH companies' investment decisions regarding large scale HPs for DH and for the marketing and sales strategies of the commercial partners.

1.6.1. Utilisation of Research Results

The focus of the scientific research in the project has been to develop analyses and results which support the decisions taken during Phase 1 by the consortium for the design bases and the HP configurations to be tested in Phase 2. The research has been conducted by two associate professors and three post.doc candidates at DTU Mechanical Engineering. In addition, three student theses have been developed under the guidance of the researchers. The group has worked on three main topics:

1. Heat pump systems and process configurations for integration with the relevant heat sources and the GCA DH system
2. Technical limitations of heat pump units
3. Comparison of absorption and vapour compression heat pumps integrated with combined heat and power plants

Short notes of the outcome of the research are included as appendices to this report.
The results of the research has been communicated and discussed with the rest of the project consortium at common workshops and individual meetings. The results of the work are at present under preparation in the form of three conference papers to be published internationally in 2016. It is expected that extended versions of these papers may be submitted for publication in international, scientific journals with open access.

1.6.2. The Project's Relevance to Energy Policy Objectives

The project is extremely relevant in a GCA and a Danish context. The GCA target of CO_2-neutral DH in 2025 is mainly fulfilled by the conversion to biomass. Since sustainable biomass is not an unlimited resource and due to the risk that biomass prices may increase in future, there is also focus on other renewable DH resources such as geothermal energy and large HP based on RES electricity. In "Heat Plan Greater Copenhagen 3" large HPs are expected to contribute with up to 250 MW to 300 MW heat capacity before 2035 and around 600 MW towards 2050.

The DK energy and climate polices with objectives for fossil free electricity and DH systems challenges the current systems – in particular, when it comes to integration of wind power. One of the main solutions pointed out is large HPs; both individual units in households and large HPs in DH systems are expected to become important.

There are currently no official objectives for HPs, but there is an understanding that the combination of biomass, solar and wind energy is not sufficient in the long run. It is expected that policies regarding an ambitious deployment of HPs will soon be developed. However, successful policy making will depend on the availability of up-scaled design and operation experience and data which this project will help providing. On an overall level, the project is in line with:

- The Energy Agreement prescribing a 100% RES in the energy system in 2050, followed up by the proposed Climate Law aiming at same target

- The Climate Plan re-stating the objective of a 40% reduction of CO_2 emission by 2020 including a RES scheme for process industries – an area where large HP would be very relevant

- The strategy for smart grids in DK, emphasizing the need for large electric HPs and electric boilers in the heating system

1.7 Project Conclusion and Perspectives

The aim of the project is to accelerate the use of large electric HPs for DH through industrial cooperation, research and experimental development. The project is the first phase of an expected large scale HP demonstration project and concerns development of technology concepts and test programs for two large-scale HPs with the purpose of demonstrating optimal design, SMART system integration, cost efficiency and maximal climate benefit. The results of the project will be used as the foundation for the second phase concerning the detailed design and construction of the two demo- HPs followed by the implementation of the test program. An EUDP application was submitted in September 2015 concerning phase 2 and funding has been granted on specified conditions.

For the HP facility based on geothermal energy the following design concept has been found relevant: A two stage Hybrid HP concept using traditional pressure stage ammonia compressors. A hybrid HP uses a refrigerant mixture of ammonia and water, providing a lower boiling point and is therefore able to operate with low pressures and better energy efficiency due to lower differential pressures when delivering high outlet temperatures.

For the HP facility based on sea and sewage water a concept with two units connected in series has been chosen each designed as two-stage ammonia refrigeration systems for optimal COP. As low winter sea water temperatures require cooling close to 0°C, a hybrid HP is not a suitable solution because it cannot be operated due to risk of freezing of the water in the refrigerant circuit.

A two-stage ammonia refrigeration system will provide more demonstration value due to the pressure required for the ammonia compressor to achieve the maximum DH supply temperature (90 °C). It will test the limits of the technology and thereby provide important knowledge as to whether ammonia compressors are suitable for these high temperature requirements of larger DH systems.
The test programs will focus on the most important parameters in terms of maturing HP technology for DH: Optimising COP (Cost efficiency) and testing SMART system integration (high supply temperatures for DH and regulation flexibility towards the power market). In addition, the largest possible components will be tested in order to explore the potential for up scaling to large-scale facilities (50-100 MW).

For the geothermal HP the specific test areas are: Optimised geothermal well performance with lower return temperatures. The increase of performance and stability of supply from the well is crucial to improving investments in geothermal energy.

For the sea and sewage HP the specific test areas are: Development of a CIP strategy to prevent fouling and optimise COP in a cost efficient way.

1.7.1 Perspectives

The results from phase 1 may be used as input, clarification and inspiration to other DH companies with interest in HP projects and can hopefully provide an overview of short cuts to some of the deliberations concerning the start up of HP projects.

The results from the second phase to follow will provide an extensive data material relevant to DH companies and the HP sector in terms of demonstration and maturing the technology. The ultimate result of the project is to develop cutting edge large HP facilities (5 MW) for the GCA, optimised in terms of COP, cost efficiency in design as well as regarding operation and SMART energy system integration.

Furthermore, perspectives for upscaling the HP design have been considered when chosing technology and components. However, the scale of the prototypes, i.e. 5 MW, will also be relevant, both in outer regions of GCA and in Denmark's large number of decentralised DH areas.

Appendix 1. - Reference list

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Appendix 2 - Publications

Published Articles in Danish Energy Media

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Appendix 3

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