Case Studies

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ANNEX 57 — Flexibility by implementation of heat pumps in multi-vector energy systems and thermal networks

Demo No.: D-001	**Location/City:** Esbjerg	**Country:** Danmark

Project name (short and full title):
60 MW seawater heat pump Esbjerg

Quotation:

Commercial project	**Year of realisation:** 2017-2023

Leader organisation (owner, constructor, solution developer, research inst., etc.): Owner: DinForsyning (Utility company, Esbjerg), consulting engineers: Added Values ApS, Heat pump manufacturer: MAN Energy Solutions

Participating organisations – demonstration project part (involved other organisations):
-

Budget of the demo (invest/monitoring etc.):
Commercial project, no information on the budget available

Summary of the project:
"Fremtidens fjernvarme"
The utility company DinForsyning in Esbjerg, Denmark is currently building the largest seawater heat pump in Denmark and the largest CO_2 heat pump worldwide (status February 2023). It has a nominal capacity of 70 MW heat and can deliver district heating at forward temperatures of 60 °C to 90 °C at return temperatures of around 35 °C. The plant consists of two identical CO_2 heat pumps in parallel. The heat pumps use a single-stage, transcritical cycle. The compressor is a turbo compressor including an expansion unit and is equipped with a variable speed drive. The evaporator is a shell-and-plate heat exchanger. The heat pump further includes a low-pressure receiver. The heat source is seawater from the North Sea that is taken in from 600 m off the coast and reinjected at 1.5 km off the coast. The nominal seawater intake is 14000 m^3/h.

The heat pump is designed to operate flexibly, i.e. it is expected to be able to ramp from minimum load to maximum load and from (hot) stand-by to full load in less than 30 seconds. The heat pump is part of the project "Fremtidens fjernvarme" (District heating of the future) of DinForsyning that further includes biomass-fired boilers, electric boilers, a large-scale battery and natural gas boilers. It will be possible to deliver frequency regulation (including primary reserve) from the heat pump alone or in combination with the other assets in the system.

Expected results

- Demonstration of the world's largest CO_2 heat pump
- Renewable district heating production and providing demand side flexibility to the electricity grid.
- Demonstration of ramping times and start-up/stop times below 30 sec.
- Demonstration of supply of different ancillary services, including symmetric services and continuously supplied services for primary and secondary reserve.

Published articles (paper, article etc.):

- https://www.man-es.com/docs/default-source/press-releases-new/man_es_pr_esbjerg_etes-heat-pump-system_eng.pdf?sfvrsn=c0b35583_0
- https://dinforsyning.dk/Admin/Public/DWSDownload.aspx?File=%2FFiles%2FFiles%2FDINFORSYNING_DK%2FKampagnesider%2FFremtidens+Fjernvarme%2FDINFORV-Projektforslag-fremtidens+varmeforsyning+20200312+med+bilag.pdf
- https://dk.ramboll.com/-/media/files/rdk/documents/energy/def/envarmepumpeivadehavetteknikogmilj04p3335.pdf?la=da
- https://addedvalues.eu/c/nyheder/havvandsbaseret-varmepumpe-bliver-hjertet-i-fremtidens-fjernvarmeforsyning-i-esbjerg
- https://en.addedvalues.eu/c/articles/fascinating-seawater-heat-pumps-in-esbjerg
- https://www.youtube.com/watch?v=4jzKzCDEnZ0

Contact information:
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Tommy Molbæk, Added values, https://addedvalues.eu/p/kontakt

Country: Denmark	**Participating Organisation:** Technical University of Denmark	**Contact/name:** Wiebke Meesenburg

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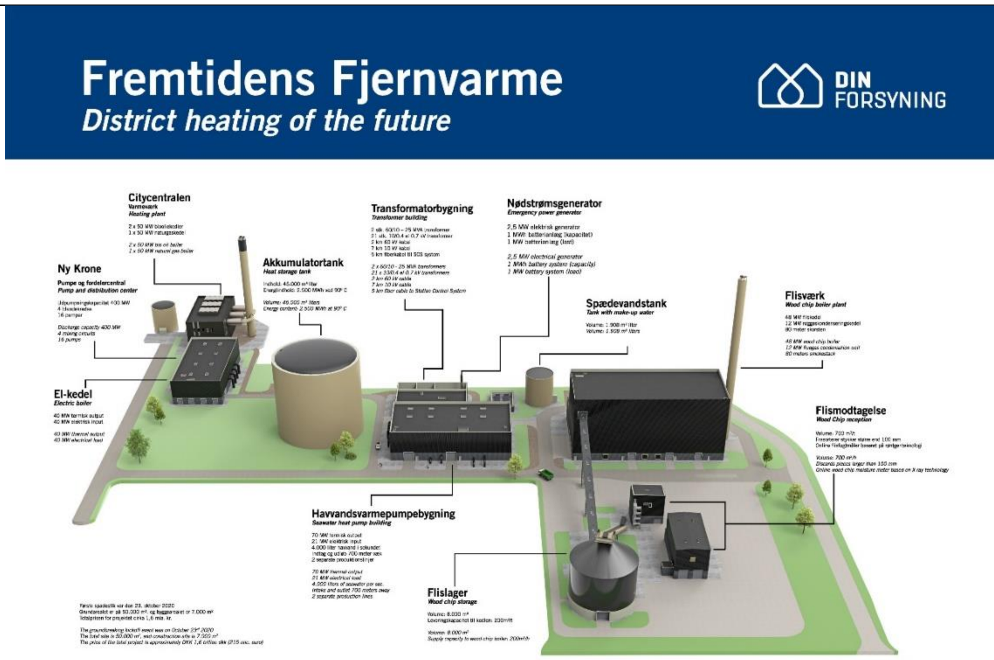
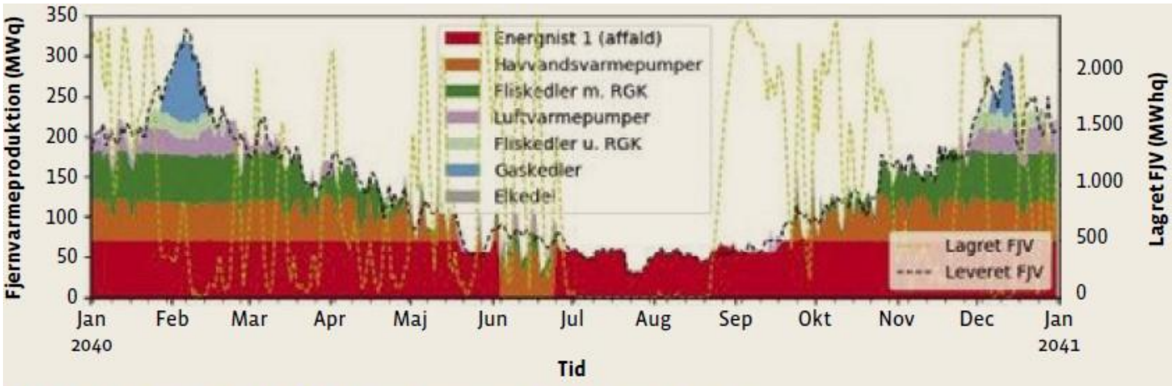


Figure 1 Overview of new district heating plant "Fremtidens fjernvarme" in Esbjerg harbour. Source: DinForsyning.



Figur 2. Eksempel på fremtidig produktionsprofil hen over et år.

Figure 2 Example of future production profile of district heating in Esbjerg, red: waste incineration plant, orange: seawater-source heat pump, green: wood chips boiler with flue gas condensation, violet: air-source heat pump, light green: wood chips boiler without flue gas condensation, blue: natural gas boiler, grey: electric boiler. Source: (Jørgensen et al., n.d.)

Homepage address: https://fremtidensfjernvarme.dk, https://addedvalues.eu/

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Project classes:

RD&D status

Large-scale demonstration	Small-scale demonstration	Lab scale (results based on measurements)	Design study (results based on simulation)
☒	☐	☐	☐

Type of heat pump

Decentralized HP (cold district heating)	Centralized HP with a district heating system
☐	☒
Heating	Cooling
☒	☐

Heat source of HP: Seawater

Power supply for HP (electricity grid, PV, wind turbine etc.): electricity grid

Buildings

New buildings	Existing buildings	Mix of new and existing buildings
☐	☒	☐
Residential	Non-residential	Mixed use
☐	☐	☒

Energy storage

Battery storage		Thermal energy storage	
Centralized	Decentralized	Centralized	Decentralized
☒	☐	☒	☐

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Control for the flexible heat pump operation

The heat pump operation is scheduled from a higher level controller optimizing the operation of the complete heat production plant portfolio.

Heat driven control[1]	Predictive control[2]	Rule based control[3]
☐	☒	☐

1. General description of the project

The district heating system in Esbjerg provides district heating to Esbjerg, Varde and Nordby. Up to now 50 % of the district heating was supplied from a coal-fired power plant. This has been taken out of operation 1. April 2023. In order to replace the heat production a new portfolio of heat producing plants is being established. It consists of two large-scale seawater heat pumps (á 35 MW_{th}) and a wood chips fired boiler with flue gas condensation(60 MW_{th}) as base load units. Further, a wood chips boiler without flue gas condensation, 2 biooil-fired boilers (á 50 MW_{th}), natural gas-fired boiler (50 MW_{th}), and electric boilers (30 MW_{th}) are included as peak load units.
The remaining district heating is mainly provided from a waste incineration power plant and further exploitation of industrial waste heat and air-source heat pumps are planned.

Figure 3 Heating central during the construction phase in early 2023. Source: DinForsyning.

[1] Operation of heat pumps to the cover heat demand depending on ambient temperatures
[2] Operation of heat pump using a model based heat demand prediction
[3] Heat pumps are controlled by a set of predefined rules (e.g. heat pump operation with blocking time)

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2. Building and system description of the project

To design the new heating central, the optimal mix of production units was determined through energy systems simulations. The new system has been designed to be flexible, with regard to fuel, supply temperatures and operation schedule. Further, it is possible to act on the ancillary service markets to support the electricity grid and generate an extra income for the system operator.

The implemented heat pump unit is the largest seawater heat pump in Denmark and the largest CO_2 heat pump worldwide (status February 2023). It has a nominal capacity of 60 MW heat and can deliver district heating at forward temperatures of 60 °C to 90 °C at return temperatures of around 35 °C. The plant consists of two identical CO_2 heat pumps in parallel. The heat pumps use a single-stage, transcritical cycle. The compressor is an oil-free hermetically-sealed HOFIM® motor-compressor unit (turbo compressor) with integrated expander by MAN Energy Solutions and is equipped with a variable speed drive. The compressor was originally developed as turbocharger for the oil and gas industry. The evaporator is a shell-and-tube heat exchanger. The heat pump further includes a low-pressure receiver. The heat source is seawater from the North Sea that is taken in from 600 m off the coast and reinjected at 1.5 km off the coast. The nominal seawater intake is 14000 m^3/h. The plant is located close to the wadden sea, which is a protected area. Therefore, it was important to choose a non-toxic refrigerant.

The heat pump has been designed to operate flexibly, i.e. it is expected to be able to ramp from minimum load to maximum load and from (hot) stand-by to full load in less than 30 seconds. In combination with other assets of DinForsyning including electric boiler, a large-scale battery and natural gas boilers, it will be possible to deliver frequency regulation (including primary reserve).

3. Energy supply – scheme of the heat supply system:

The two heat pump units are set up in parallel, with the possibility to couple them in series on the high temperature side. The heat supplied from the heat pumps at 60 °C to 90 °C may be delivered directly into the district heating grid or upgraded by the wood chip fired boilers or the peak load units (electric boiler, natural gas boiler, wood chips fired boiler without flue gas condensation, bio-oil boiler). Further, a storage tank of 45.000 m^3 (corresponding to 2500 MWh at 90 °C) is included in the system. The tank may be used to optimize the operation schedule of the plants.

The overall plant is controlled by a high-level controller optimizing the operation schedule for the different plants, including optimization of which markets to act on.

4. Flexibility – scheme and control strategy of the system:

The combined plant has been designed to be flexible with regard to fuels, operation schedule, delivered forward temperature, and the possibility to act on different ancillary service markets.

The heat pump system has been designed to ramp up from 0 % to 100 % load and down from 100 % to 0% in less than 30 sec. The ability of the compressor to ramp up and down this quickly has been demonstrated in the FAT test at MAN Energy solutions for a load change of 100 % to 25 % and from 25 % to 100 %(Wolscht et al., 2023). The demonstration of these ramping times on the actual plant is still missing. The expected ramping times allow for participation in different regulation power and frequency reserve markets, including primary frequency reserve. Continuous regulation is possible.

It is to be demonstrated how fast the heat pumps can ramp-up and down in the actual operation, and how the system performance (COP) is affected by the flexible operation.
Which markets the heat pump will act on is decided by the high level controller optimizing the economic performance of the overall system.

5. Description of the business model with a flexible HP-operation

The variety of different units included in the “Fremtidens Fjernvarme” system enables to minimize the operational cost as it reduced the dependency from a single fuel. The systems operation is optimized according to the day-ahead electricity market as well as the projected heat demand and forward temperature in the district heating system. The possibility to act on different ancillary service markets may be included in the economic optimization.

The ancillary service markets are subject to development in Denmark and there is some uncertainty, which will be the most interesting ones for the heat pump to act on in future. Western Danmark, where Esbjerg is located, is part of the DK1 regulation zone that is connected to the Continental Europe Synchronous Area. Here, the ancillary services comprise frequency containment reserve (FCR, primary), automatic frequency restoration reserve (aFRR, secondary), and manual frequency restoration reserve (mFRR, tertiary). The heat pump system is large enough to potentially act on either of the three markets. FCR and aFRR require a symmetric service, i.e. the system needs to be able to regulate up and down (corresponding to a reduction in power consumption and an increase in power consumption). The symmetric service can be delivered by pairing the heat pump system with the electric boiler and/or the battery in the system.

The variation in heat production due to the provision of ancillary services can be buffered by the hot water storage included in the system. Further, the non-electric boilers may support in case too little heat is available from the heat pump. The duration of up-regulation (i.e. increased power uptake) is however limited by the available storage capacity and the heat demand in the district heating system.

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6. Results of the project

The project is a commercial project. Nonetheless, there are several potential outcomes that may be of value to both stakeholders of future projects and academia. These include:

- The build heat pump is first of its kind both in terms of size and flexibility. The project will demonstrate the large-scale heat pump. The monitoring of the performance of the heat pump cycle and the effectiveness of the expecting fouling is expected to deliver valuable inputs for future similar projects.

- A major advancement of this project is the expected demonstration of fast regulation of the heat pump to provide primary frequency reserve. The demonstration of this operation mode will further allow to quantify the effect of flexible operation (fast regulation, idle operation, additional storage losses, etc.) on the system's COP.

7. Challenges / socio economical barriers and opportunities

No information available.

8. Additional information: Flexibility options

The large-scale CO_2 heat pump is able to adapt the power uptake quick enough to potentially supply primary frequency reserve on European markets. (Wolscht et al., 2023) showed that the heat pump unit test bench at the manufacturers site was able to change the power uptake of the compressor from 100 % to 25% and from 25 % up to 100 % within 30 seconds, respectively. The interaction with the sink and source streams on-site in Esbjerg remain to be investigated.

The plant is further flexible with regard to the supplied temperature levels. As mentioned above the supply temperature from the heat pump may be between 50 °C and 90 °C (AddedValues, n.d.). Ensuring low return temperatures is essential to ensure a high coefficient of performance. During cold periods, the operational range of the heat pump may further increased by preheating the source water using the district heating return and heat from the flue gas from the wood chips boiler. Thereby, frosting may be prevented and the heat pump can be kept in operation even at sea water temperatures close to the freezing point (Jørgensen et al., n.d.).

References

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Wolscht, L. ; Knobloch, K. ; Jacquemoud, E. ; & Jenny, P. (2023). Dynamic Simulation and Experimental Validation of a 35 MW Heat Pump Based on a Transcritical CO 2 Cycle. *Citation*, 93–105. https://doi.org/10.17185/duepublico/77273