Case Studies

https://heatpumpingtechnologies.org/annex57/

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):
EnergyLab Nordhavn, FlexHeat

Quotation:

Schedule of the demo project (research study): 2015-2019	**Year of realisation:** 2018

Leader organisation (owner, constructor, solution developer, research inst., etc.):
HOFOR

Participating organisations – demonstration project part (involved other organisations):
Section of Thermal Energy - Technical University of Denmark

Budget of the demo (invest/monitoring etc.):
N/A

Summary of the project:
The establishment and analysis of the FlexHeat heat pump was realized as part of the research and demonstration project "EnergyLab Nordhavn" that studied solutions for integrated energy systems in urban environments in a living lab established in the newly built area Nordhavn in Copenhagen, Denmark.

The FlexHeat heat pump was established in 2018 in the outer Nordhavn area. It is owned and operated by the local utility company HOFOR. The heat pump is an 800 kW two-stage ammonia heat pump that supplies heat to four cruise-ship terminals and a large-scale warehouse via a local district heating grid. The system further includes two electric heaters á 100 kW each and a 100 m^3 hot water storage tank.

The system has been designed to allow for flexible operation of the heat pump. This includes optimization of the operation schedule and potentially also providing frequency reserve to the power grid.

Expected results

- Demonstration of potential to operate the heat pump flexibly in coordination with the electric heaters and the large-scale storage.
- Development of control that allows for fast load adaption of the heat pump.
- Demonstration of the achievable ramping times.
- Analysis of the economic potential of providing ancillary services to the power grid.

Published articles (paper, article etc.):

- Kjeld, T. F. G., & Meesenburg, W. (2019). EnergyLab Nordhavn - Delivery no.: WP5.3 – Protocol for intelligent management of heat accumulators (pp. 1–36). http://www.energylabnordhavn.com/deliverables.html
- Kjeld, T. F. G. (2019). EnergyLab Nordhavn - Delivery no.: D5.5a - Optimum supply of an island district heating grid by a local heat plant. http://www.energylabnordhavn.com/deliverables.html
- Kjeld, T. G., & Meesenburg, W. (2019). EnergyLab Nordhavn - Deliverable no.: 5.5b Manual for optimized operation of an island district heating grid. http://www.energylabnordhavn.dk/deliverables.html
- Meesenburg, W., Kofler, R., Ommen, T., Markussen, W. B., & Elmegaard, B. (2019). Design considerations for dynamically operated large-scale ammonia heat pumps. 25th IIR International Congress of Refrigeration. https://doi.org/10.18462/iir.icr.2019.1203
- Meesenburg, W., Markussen, W. B., Ommen, T., & Elmegaard, B. (2020). Optimizing control of two-stage ammonia heat pump for fast regulation of power uptake. Applied Energy, 271, 115123. https://doi.org/10.1016/j.apenergy.2020.115126
- Meesenburg, W., Ommen, T., & Elmegaard, B. (2018). Dynamic exergoeconomic analysis of a heat pump system used for ancillary services in an integrated energy system. Energy, 152, 154–165. https://doi.org/10.1016/j.energy.2018.03.093
- Meesenburg, W., Ommen, T., Markussen, W. B., & Elmegaard, B. (2020). Influence of component sizing on the dynamic behaviour of fast-regulating two-stage ammonia heat pumps. ECOS 2020 - Proceedings of the 33rd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, 923–934.
- Meesenburg, W., Thingvad, A., Elmegaard, B., &; Marinelli, M. (2020). Combined provision of primary frequency regulation from Vehicle-to-Grid (V2G) capable electric vehicles and community-scale heat pump. Sustainable Energy, Grids and Networks, 23, 100382. https://doi.org/10.1016/j.segan.2020.100382

Case Studies

https://heatpumpingtechnologies.org/annex57/

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Contact information:
Kristian Honoré, HOFOR

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

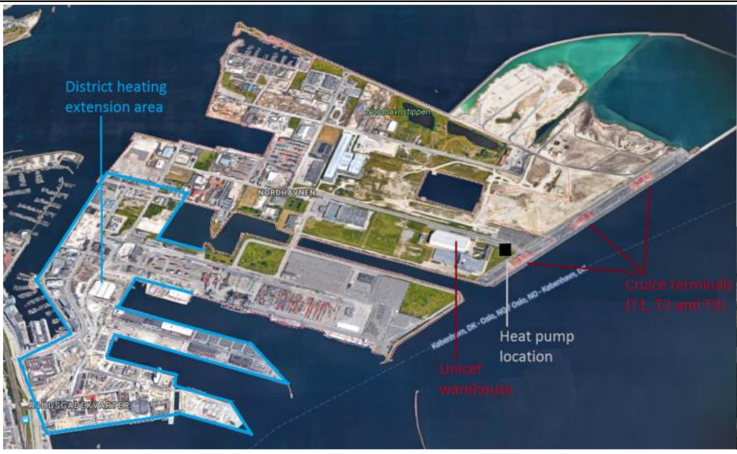

Figure 1 Location of heat pump, cruise ship terminals, and warehouse in Nordhavn, Copenhagen

Figure 2 FlexHeat heat pump building and storage tank in front of cruise ship terminal building. Source: HOFOR

Homepage address: www.energylabnordhavn.com/

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

IEA Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)

Delivered by:
Team Denmark

Case Studies
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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
☐	☐	☒	☐

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 EnergyLab Nordhavn project was a large-scale project combining research, development and demonstration activities on solutions to transform the energy system to efficiently integrate large shares of renewable energies by sector coupling. The integration of multiple energy sectors (electricity, heat and transport) was studied using the newly built Nordhavn area in Copenhagen as a living lab. The project ran from 2015 to 2019 and had a total budget of DKK 143 mio. (€ 19 mio.), of this DKK84 mio. (€ 11 mio.) funded in two rounds by the Danish Energy Technology Development and Demonstration Programme (EUDP).

As part of this living lab, the FlexHeat system was established to supply heat to a small-scale islanded district heating grid in the outer Nordhavn area. The system was designed to allow for a high degree of operational flexibility, including the heat pump equipped with variable speed drive, fast-reacting electric boilers and a heat storage tank to allow decoupling the heat production from the heat demand. The aim was to demonstrate the ability to operate 1) according to the heat demand in the grid, 2) minimizing the electricity cost by reacting to the electricity spot market prizes, 3) supplying congestion management services to the distribution system operator, 4) supplying frequency regulation services to the transmission system operator, 5) in combination with other fast regulating assets.

[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)

Case Studies

https://heatpumpingtechnologies.org/annex57/

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

2. Building and system description of the project

The FlexHeat heat pump is a two-stage ammonia heat pump with a thermal capacity of 800 kW delivered by Johnson Controls and installed in the Nordhavn harbor area in Copenhagen, Denmark. It is owned and operated by HOFOR and was part of the EUDP research and development project EnergyLab Nordhavn. It uses groundwater at 10.5 °C as heat source and rejects the groundwater into the sea. The heat pump is the main supply unit of a small-scale district heating grid supplying three cruise ship terminals and a high bay warehouse. The heat pump can deliver district heating forward temperatures of 60 to 82 °C. The heat supply unit is further equipped with a storage tank with a volume of 100 m³ and two electric boilers with a capacity of 100 kW each downstream of the storage tank.

The heat pump unit is comprised of the following main components: flooded evaporator, separator, low- and high-stage piston compressor, open flash intercooler, desuperheater, condenser and subcooler and two throttling valves. The evaporator was a corrugated plate heat exchanger, and the other three heat exchangers were shell-and-plate heat exchangers. Both compressors are equipped with variable speed drive, thus enabling part-load operation.

An intelligent operation optimization was implemented, to allow for an optimal bidding strategy including day-ahead and frequency regulation market. This allows for cost-optimal operation of the heat pump system.

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

The heat pump supplies heat to a local district heating grid. The grids design temperatures are forward temperatures of 65 °C to 70 °C and a return temperature of max. 45 °C during the heating season and 65 °C forward and 30 °C return outside the heating season. To ensure low return temperatures to the heat pump (and thereby achieve a high coefficient of performance) the customers connected to the grid were counselled regarding the optimization of their district heating substations. Thereby, it was possible to reduce the return temperatures by 10 K - 15 K for all customers.

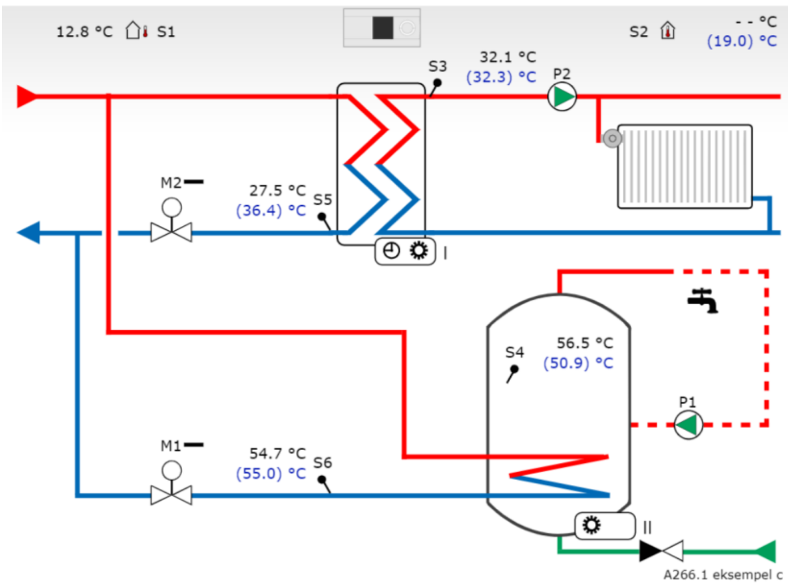

Figure 3 The ECL 310 portal from Danfoss to supervise and control the heat supply to the cruise-ship terminals

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

The heat pump system is able to run in 7 operational modes representing the demonstration of the different types of flexible operation described above.

1. The heat pump runs at a given capacity and based on the consumption level, the remaining heat is delivered into the tank
2. The same as mode 1, but the temperature to the costumers is boosted to a higher level by the electric boilers if needed.
3. Same as in mode 1 but with different settings for the tank and heat pump. Mode 1 is used as a default mode whilst mode 3 is used for tests.
4. The heat pump is not running. The storage tank discharges heat to the costumers.
5. Same as in mode 4, but the temperature of the discharged heat from the tank is boosted by the electric boilers to a sufficient level.
6. The heat pump is not running. The return water is circulated through the electric boiler to boost the temperature in the bottom of the tank while discharging the tank.
7. Similar to mode 1, but here the power uptake of the heat pump is controlled directly to allow for fast reaction to signals from the TSO.

It was found that it would be economically interesting to be able to supply FCR-N frequency regulation service. This is a service requiring a symmetric adaption of the load depending on the signal from the grid.

The required ramping times are 150 seconds to regulate to the bid maximum/minimum capacity. The minimum bid size is 0.3 MWel. This is larger than the electric capacity of the FlexHeat heat pump. Since two-stage ammonia heat pumps are however common in Denmark as district heating units (also in the MW range), it was deemed interesting to test whether it could be possible to deliver this services with this kind of plant.

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

An intelligent optimization model has been implemented by HOFOR to optimize the heat pump system operation. This included the development of a heat demand profile by training a machine learning model on weather data and consumption data. A regression model of the forward and return temperatures in the grid was developed depending on the flow, heat demand and heat pump operating conditions. These two models combined with an electricity price forecast were fed into an optimization model of the heat pump system (including heat pump, electric heaters, and storage) to optimize the operation schedule. After an analysis of economically interesting markets, the option to provide ancillary service (FCR-N service) was suggested as an add-on to the optimization algorithm.

Since utility companies in Denmark are legally obliged to operate their systems non-profit and to choose the socio-economically most feasible supply options, any reduction of the operational cost will directly reflect back on the district heating prices. In this way, flexibly operated heat pumps that can react to low electricity prices due to large shares of renewable energy in the grid can contribute to securing low heat prices to the customers and help to accommodate large shares of renewable electricity in the heat production.

Case Studies

https://heatpumpingtechnologies.org/annex57/

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

6. Results of the project

The operation of the system in all operation modes and the cost optimal operation planning was demonstrated as part of the EnergyLab Nordhavn project. The DSO services were studied as part of the DREM project (drem.dk). To allow for provision of frequency regulation services (FCR-N) to the TSO, the control of the heat pump was changed to allow for a direct control of the power uptake. Despite the heat pump being too small to bid into the frequency reserve markets alone, it was demonstrated that it is possible to supply secondary frequency reserve and possibly also the “slow” primary frequency reserve FCR-N which requires regulation times of 150 s to the full bid size. Calculations for the year 2018 showed that the heat production cost could be reduced by 6 % by optimizing the operation schedule (without provision of ancillary services), while the provision of FCR-N frequency regulation would have further reduced the heat generation cost by another 7 %.

To allow for shorter reaction times, while keeping the large regulation capacity provided by the district heating grid (due to the large thermal capacity in the storage and the grid), it has been proposed to deliver a combined frequency regulation service from the heat pump and quick regulating units. The technical and economic feasibility has been shown through simulation studies for the combination of the heat pump with a pool of electric vehicles. For the year 2018, the additional income was 4740 €/a, compared to additional operation cost of the heat pump and electric vehicle charging of 2961 €/a and 750 €/a, respectively. The achievable net surplus was found to be highly dependent on the future development of the capacity payments granted for delivering the FCR-N service.

7. Challenges / socio economical barriers and opportunities

Power system perspective

Unlocking the large flexibility that lies within thermal storages, the district heating grid and the buildings connected to it by using heat pumps, can help to accommodate large shares of renewable electricity in the system and to decarbonize the heat supply. The described case study has shown that it may be economically advantageous for large-scale heat pump operators to not only optimize their consumption pattern according to spot market prices, but to also act on ancillary service markets. This has the potential to reduce the heat generation cost and thereby the cost of district heating for the consumers. The Danish TSO Energinet expects that the need for flexible capacity, as well as the number of flexible units in the grid will increase. The exploitation of this flexibility will be essential when going towards 100 % renewable electricity, but also means that the complexity of operating the system will increase (Energinet, 2022)

Large-scale ammonia heat pumps

Fast regulation of large-scale ammonia heat pumps with flooded evaporators requires additional measures to prevent liquid entering the compressors due to suddenly increasing evaporation pressures during fast ramp down. It has been further observed that large-scale ammonia heat pumps have not been designed to be able to ramp up and down very quickly, since this has not been in focus before. As seen in this project, it requires a dedicated control set-up to allow for relatively fast regulation. The ramping times are however limited by the thermal capacity of the system, wherefore it is deemed unlikely that large-scale ammonia heat pumps will be able to provide primary frequency reserve with reaction times of 30 s or lower on their own. The combination with other fast regulating units could however unlock the large thermal capacity that the heat pumps have access to, to provide ancillary services

Energinet. (2022). PATHWAYS TOWARDS A ROBUST FUTURE ENERGY SYSTEM. https://energinet.dk/media/y5rhoqjy/pathways-towards-a-robust-future-energy-system_energinet-2023-01-23.pdf