# Final report

## 1. Project details

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|---|---|
| **Project title** | EnergyLab Nordhavn, Smart Components in Integrated Energy Systems |
| **Project identification (program abbrev. and file)** | EUDP 64015-0055 |
| **Name of the programme which has funded the project** | Energiteknologisk Udviklings- og Demonstrationsprogram |
| **Project managing company/institution (name and address)** | DTU Elektro, Center for El og Energi<br>Bygning 325, 2800 Kgs. Lyngby |
| **Project partners** | Danfoss, ABB, DTU BYG, DTU MEK, DTU Elektro, PowerLabDK, |
| **CVR** (central business register) | 30060946 |
| **Date for submission** | March 26, 2021 |

## 2. Short description of project objective and results

Gennem tre demonstrationer har projektet vist

- hvordan varmepumper til boost af brugsvandsforsyning og til forsyning af cirkulationskredsløbene på samme tid kan muliggøre forsyning af moderne bygninger med ultralavtemperatur fjernvarme og agere som fleksibel forbruger på el og fjernvarme-siden;
- hvordan varmeforbruget i lejlighedsbyggeri kan kontrolleres mhp at udjævne spidsbelastninger i fjernvarmenettet uden at gå på kompromis med beboernes komfort, og hvordan sådanne løsninger samtidig kan forbedre balance og drift af varmeleverancen lokalt;
- hvordan overskudsvarme fra supermarkeders køleanlæg kan bringes i anvendelse i fjernvamenettet;

og hermed fremtaget en portefølje af tekniske løsninger til integreret design og drift af boliger, supermarkeder, fjernvarme- og elinfrastruktur.

Through three demonstrations, the project has shown

- How heat pumps for boosting the supply and circulation of domestic hot water enable the supply of modern buildings with ultra low temperature district heating, while at the same time act as flexible electricity and district heating consumers;
- How space heating may be controlled to support shaving of peak loading of the district heating network, without compromising residents' comfort. It has also been shown how such solutions allow an improved optimization of the local heat management;
- How excess heat from refrigeration units in supermarkets can be utilized in the district heating network;

And thus established a portfolio of technical solutions for the integrated design and operation of dwellings, supermarkets, district heating and electricity infrastructure.

## 3. Executive summary

The *EnergyLab Nordhavn – Smart Components in integrated energy systems* project has aimed to enable and demonstrate specific Danfoss heating and cooling components' ability to contribute to the integrated operation of the energy system (including electricity and district heating), while maintaining their primarily heating and cooling service functions.  This aim supports the transformation of the energy system to a reliable, cost-effective and sustainable system based on renewable energy utilizing the benefits of closely integrated and coordinated energy infrastructures.  The project has done so based on Nordhavn as a highly visible real-life laboratory, yielding a number of results, including the following specific demonstrations

- Through the use of home automation systems, it has been demonstrated how varying energy needs and the thermal capacity of buildings can be exploited to support a district heating utility in reducing the need for peak load boilers. This will help realize a district heating system being 100 % CO2-neutral and thereby contribute to realize the Copenhagen 2025 climate plan for district heating.
- Using booster heat pumps for the supply of domestic hot water in housing blocks ensures a low return temperature and enables the use of ultra-low district heating forward temperatures. It has been shown how the flexibility of the local heat demand and the heat store allows the heat pump to act as a flexible electricity and district heating consumer.
- Surplus heat from a supermarket has been delivered to the district heating network through the advanced control of a CO2 based heat recovery unit, and it has been demonstrated how this system can be operated to allow for an acceptable return of investment for the supermarket operator.
- The project has contributed to the build-up of an energy data warehouse that supports secure real-time data sharing between the stakeholders, thus supporting the realization of a smart energy system encompassing electricity, heat, buildings, transport, and residents. The ability of the system to support real control applications has also been demonstrated.

Furthermore the project has leveraged the global visibility and the further innovation triggered by being integrated with other EnergyLab Nordhavn technology demonstrations, building up a living lab ready for further experimentation with coordinated operation of diverse assets in the energy system.

Thus, the project has been successful in creating job enhancement, increasing the competitiveness and export possibilities for the industrial partners, while contributing with key solutions for unlocking flexibility and contributing to the decarbonization of district heating and electricity supply.

## 4. Project objectives

The project set out to result in substantial commercial impact by leading the way for new innovative products, and societal impact by developing solutions for a future energy system for sustainable cities based on renewable energy. It was designed together with other activities and implemented in Scandinavia's largest city development area with energy infrastructure and construction projects at all stages.

This particular project aimed to enable selected Danfoss heating and cooling components and systems (thermostat valves, district heating substation and supermarket cooling compressors) the ability to be operated as part of an optimised operation of the integrated energy system in Nordhavn (including electricity and district heating), without compromising their primary heating and cooling service functions. This functionality was set to be provided by the combination of 1) dynamically identification and communication of the components / systems actual energy flexibilities; 2) dynamically information of the energy systems need's; and 3) dynamically, coordinated regulation of their operations with respect to the energy systems need's and maintaining the primary energy services.

The Danfoss components included in the project were 1) Heat pumps, designed for boosting the ultra-low district heating temperature (<50°C) for hot tap water heating (>50°C) and optionally for heating; 2) Remote controlled valves, regulating the water flow for space heating (or cooling) services; and 3) Heat pumps, designed for refrigeration in supermarkets.

The project was implemented for integrated activities together with the larger EnergyLab Nordhavn, new Urban Energy Infrastructures. Hence - for practical reasons the work package was renamed to WP 10, comprised of three tasks:

- Heat Booster Substation (HBS) based on ultra-low temperature district heating (ULTDH), providing domestic hot water for multifamily or commercial buildings, including heat pump for providing domestic hot water and heating **and** a circulation Booster, boosting the DHW circulation water from 50°C to 55°C. (WP 10.1)
- Remote controlled valves for regulation of a water based building space heating. (WP 10.2)
- Utilisation of spare heat pump (compressor) capacity in supermarkets and the utilization of the generated excess heat. (WP 10.3)

These tasks were carried out partly through rather independent activities related to the establishment and initial testing of the physical pilot equipment and partly with cross-cutting activities to ensure the integrated development of solutions for low temperature and ultra low temperature disctrict heating contributing also to the provision flexibility services for the electrical grid.

**Milestones**

| Technical and commercial Milestones | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|
| MP0: Consortium Agreement signed | x | x | | | | |
| MP1: Contracts signed with building owners | | x | | x | | |
| MP2: Heat boosters successfully installed in building | | | x | x | | |
| MP3: Heat booster and circulation HP successfully demonstrated | | | | x | x | |
| MP4: Living Connect successfully installed in 10 apartments | | | x | | | |
| MP5: Living Connect successfully demonstrated | | | | | | x x |
| MP6: Multi-purpose heat pump successfully installed in supermarket | | | | | x | x |
| MP7: Multi-purpose heat pump successfully demonstrated | | | | | | x |
| Commercial milestones - ELN II | | | | | | |
| MC1: Commercial potentials of heat booster clarified | | | | | x x | |
| MC2: Commercial potentials of system response of Livng Connect clarified | | | | | | x |
| MC3: Commercial potentials of multi-purpose utilisation of heat pump clarified | | | | | | x |

The project reached almost all milestone. Only the demonstration of use of supermarket excess heat incurred such delays that two milestones were not met by the end of the project. These are MP7 and MC3. Regarding MP7, the testing did start and continued after the project ended. At time of writing, it has been tested that heat export to DH is working, but due to lack of CO2 filling in the compressor, system temperatures for heat export to DH is not available in general.. Regarding MC3, the commercial potentials have been analysed, but since they could not be aggregated with the technical demonstration within the project period, also this milestone is marked read. However, the results are promising and the system has been taken into further maturation through the creation of 180 product codes and a subsequent sale of about 100 units, mainly in DK. See section on utilization of project results for further information.

The main risks identified at the start of the project were
**Recruitment of building owners:**

Through early efforts and collaboration with Balslev and HOFOR, timely recruitment of demonstration sites for the heat booster substation in Havnehuset Vest (10.1) and for the home automation in Havnekanten (10.2), these two tasks did not suffer significantly. However, the first attempt to line up with Netto in Lüders P-hus as supermarket (10.3) failed, which was the primary reason for the accumulated 19 months project extensions applied for and granted. Also a compromise had to made in that it was not possible to establish an alternative heat source in this demonstration.

**Uncertainty in application budget for installations and experiments**

This was handled through a number of budget adjustments.

## 5. Project results and dissemination of results

The project results end dissemination will be reported in 3 subsections according to the task structure:

**Heat Booster Substation (HBS) and Circulation Booster (CB), WP 10.1:**

The developed **Heat Booster** system (HBS) has operated successfully for 2,5 years, showing the performance expected. The detailed operational data has been analyzed and is among others giving the insight in the seasonal influence of the operation. On project completion, the system has been stopped and the original domestic hot water system is operating instead. Still the system remains in Havnehuset for optional future test purpose. E.g. test of increased COP by change of refrigerant in the heat pump.

*Figure 1: (left) Colleagues from Danfoss and HOFOR together with local residents at Havnehuset vest. (Right) Torben Ommen and Rongling Li explain the system function to the deputy mayor of Beijing, Sui Zhenjiang. Booster solutions like this enable the use of ultra low temperature district heating, use of excess heat and are also obvious flexible electricity consumers.*

The research at DTU Mechanical Engineering focused on the integration of booster heat pump substations with the required ultra-low temperature district heating system. It was assessed how the type of the central heat plant influences the thermodynamic performance and economic feasibility of the proposed solution (Ommen et al., 2017). Further, it was investigated how the boundary conditions of the supplied area influences the socioeconomic feasibility of the supplied solution (Meesenburg et al., 2019). Both studies were related to WP.10.1 as well as WP 5.2 (Heat supply infrastructure) in the project ”EnergyLab Nordhavn - NewUrban Energy Infrastructures” (project number: 64014-0555). The studies showed that ULTDH with booster heat pumps may lead to improved thermodynamic performance of the overall system if the central heat supply plant is a heat pump. In this case, the performance is improved as the performance of the central heat pump increases with decreased network temperatures and the heat losses from the system decrease with decreased network temperatures. However, it was shown that socioeconomically ULTDH suffers from double investment in district heating and decentral supply infrastructure compared to LTDH. It was further seen that ULTDH can only be competitive for areas with high heat demand density and relatively high space heating demands. In order for ULTDH with decentral booster heat pumps to become more competitive, the investment cost and operation and maintenance cost of the booster heat pumps need to be reduced and the performance increased.

As part of the project several Bachelor projects were completed on the booster heat pump test rig built at DTU. This looked into building of the testrig itself and modelling and experimental assessment of the dynamic behaviour of the booster heat pump. It was seen that the start-up times of the system are small and the system could be used to turn on and off quickly if needed, e.g. by operating according to electricity price signals or to provide ancillary services as part of an aggregated pool of flexible units. The model and experimental data showed however some differences in off-design behaviour, which could not be explained from the available data. Research on the topic has been continued in the HPMixPerform project.
We successfully used the system to test model predictive control (MPC) concepts developed by a MSc. project student, demonstrating a working and relevant economic, MPC control implementation, and a non-linear generic solver algorithm was developed based on MATLAB, with the aim to improve the forecast of domestic hot water consumption. ´

The developed **Circulation Booster system** (CB) has operated successfully for 1,5 years. The system has now been turned off and the original circulation domestic hot water heating system via the storage tank is operating instead. Still the system remains in Strandboulevarden for optional future test purpose. E.g. application optimization and test of increased COP by change of refrigerant in the heat pump.

*Figure 2. The circulation booster system installed at Strandboulevarden site.*

Operational data has been analyzed with the aim to give additional and more detailed input to the economic feasibility of the concept. Also for this concept the seasonal influence has been measured and analyzed. With the current tax on electricity for heating/DHW and ventilation, the direct payback time of the CB is 5 years. Meaning today there is a OK investment case for the CB concept, based on the operational data from Strandboulevarden. Going ahead with a higher bonus for a lower DH return temperature the payback time will be shorter.

### Dissimination related to the HBS:

Jan Eric Thorsen et al, *Load Shift Experience with ULTDH Substation for Multifamily Building.* 4 th International Conference on Smart Energy Systems and 4th Generation District Heating Aalborg, 13-14 November 2018:

Jan Eric Thorsen et al, *SMART OPERATION OF ULTDH BOOSTER SUBSTATION FOR MULTIFAMILY BUILDING.* 5th International Conference on Smart Energy Systems, Copenhagen, 10-11 September 2019, #SESAAU2019:

Jan Eric Thorsen et al, *EXPERIENCE WITH BOOSTER FOR DHW CIRCULATION IN MULTi APPARTMENT BUILDING*, 6th International Conference on Smart Energy Systems, Digital, 6-7 October 2020, #SESAAU2020:

Jan Eric Thorsen et al, *Experience with smart operation of ULTDH Booster Substation for multifamily building*, 50th International HVAC&R Congress and Exhibition, Belgrade, 4–6 Dec. 2019:

*ULTDH Substation for multi apartment building,* EUROHEAT & POWER magazine, I/2019,

Ommen, T., Thorsen, J.E., Markussen, W.B., Elmegaard, B., 2017. *Performance of ultra low temperature district heating systems with utility plant and booster heat pumps*. Energy 137, 544–555. https://doi.org/10.1016/j.energy.2017.05.165

Meesenburg, W., Ommen, T., Thorsen, J.E., Elmegaard, B., 2020. *Economic feasibility of ultra-low temperature district heating systems in newly built areas supplied by renewable energy*. Energy 191. https://doi.org/10.1016/j.energy.2019.116496

Zühlsdorf, B., Meesenburg, W., Ommen, T.S., Thorsen, J.E., Markussen, W.B., Elmegaard, B., 2018. *Improving the performance of booster heat pumps using zeotropic mixtures.* Energy 154, 390–402. https://doi.org/10.1016/j.energy.2018.04.137

Furthermore results on the Heat booster substation has been presented at approx. 15 other occasions.

**Remote controlled valves for regulation of a water based building space heating. (WP 10.2):**

Danfoss Link Controllers for smart control of floor heating systems where installed in 85 appartments in the Havnekanten building. A MSc student analyzed the performance of the floor heating systems based on measured data and simulations. The student identified the load shift potential as well as the negative impact of scheduled daily temperature changes on peak demand. Also the effect on return temperatures to the DH network was addressed and a novel system solution was proposed. The potential of this system was investigated and the requirements for future designs of robust floor heating systems was described. The implementation of the load shift and provided troubleshooting services have been analyzed by DTU BYG so that Danfoss could rectify their implementation. This led to a successful implementation of the load shifting concept based on automated generation of set points using a Matlab script. The new setpoints reduced heating entirely during the peak period with a negligible effect on indoor temperatures, which provides an potential source of energy flexibility with minimal consequences.

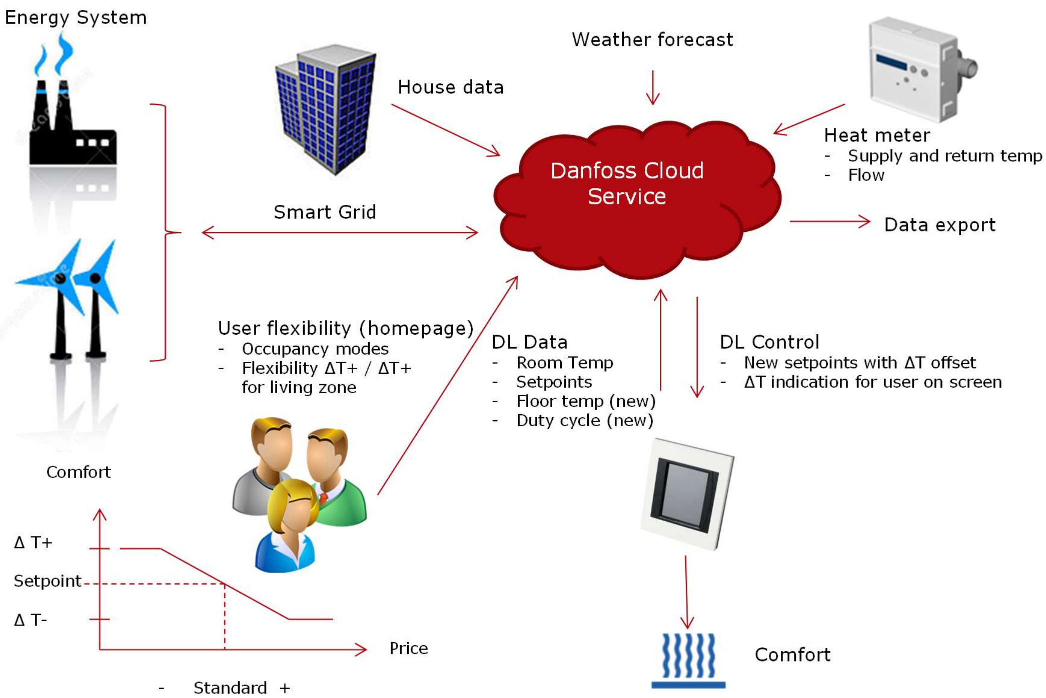



*Figure 3: The logic of the Danfoss link based control architechture.*

The project achieved its goal for the activities on home automation systems by successfully demonstrating a complete reduction in heating consumption in several apartments during the peak heating period. This was based on a Matlab script, which gave offsets to temperature set points. The script could be customized for different apartments and room types. However, the analysis also brought several important learnings related to occupants' behavior. Many occupants used their programmable thermostats to schedule setpoints that changed throughout the day. For the same reason that we could shift the load entirely away from the peak period with no impact on thermal comfort, the scheduling of higher setpoints during the peak period had the effect of only demanding heat during these periods and not at all during the off-peak periods, even though the heat was released at a nearly constant rate throughout the day. The first step in offering flexibility to the DH grid is to reduce these unnecessary peaks in demand by removing the possibility to schedule hourly setpoint changes to floor heating systems embedded in concrete. The floor heating data also revealed that occupants prefer to have higher temperatures in the bathroom, which was expected. But the data showed the occupants often did not achieve these higher temperatures in bathrooms because the bathroom doors were left open. For this reason, the floor heating in the bathroom ran continuously, and in many cases heated the other rooms above their setpoint. This high constant flow in the bathroom would lead to high return temperatures since the hot water did not have a chance to cool, so the project recommended a focus on closing bathroom doors to improve heating performance. This was confirmed through simulations. Through analysis of data, the project also detected several installation errors in apartments, such as thermostats swapped between rooms, which caused constant heating in a room with the wrong temperature sensor. Another example was a constantly closed valve, so the loop never received warm water. Through this analysis it was possible to see that the hot water temperature was more-than-sufficient to meet normal demands. The property inspector had increased the hot water supply temperature from 35 degrees C to 40 degrees C in response to complaints. This resulted in a higher return temperature to the DH network, but this increase seemed unnecessary based on the analysis of measured data. If bathroom doors are closed, it should be possible to supply much lower temperatures to the heating system, which in turn lowers the DH return temperature. The lower DH temperature is important to the DH provider since it reduces the hydraulic requirements of the system and furthermore increases the heat output of production from condensing biomass boilers. To realize a system with low supply and return temperatures, a system with local mixing loops for each bathroom loop as well as a mixing loop for all other rooms in each apartment was pro-posed. Calculations on a cascade system that would use the return hot water from the bathroom as supply for other rooms were performed. This would offer the lowest possible return temperatures, but the analysis indicates that this is likely overkill and that simple local mixing loops with maxi-mum temperature constraints will likely provide the most robust and cost-effective solution. This would help to solve many of the problems outlined above.

**Utilization of waste heat and spare heat pump capacity, WP 10.3:**
Installation of the Heat Recovery Unit (HRU) and connection to the district heating network was only achieved rather late in the project. The delays caused by lack of common technical understanding, coordination and communication between many involved stakeholders, for some of which the demonstration was not of crucial importance, including unforeseen delays related to formal approvals etc.
A Bachelor project (Rørbæk Kruse and Abdikarim Ali, 2020) addressed a use case where heat is recovered from the supermarket in order to supply district heating (winter temperatures 80 °C forward / 45°C return, summer temperatures 65 °C forward / 30°C return), space heating and domestic hot water to the supermarket building or both. The different scenarios were compared to the cooling only case based on an economic optimization of the operation in every hour of the year. Within a sensitivity analysis it was further assessed what the influence of a change in the district heating substitution price, the electric heat tax, the electricity prices and the district heating supply temperatures is. It was found that provision of district heating alone is not economically feasible since the investment cost in the additional heat exchanger is not earned back by selling district heating. Providing heat to the supermarket for internal use results in a saving, which can be slightly increased if district heating is supplied additionally. The sensitivity analysis showed that the heat recovery from the supermarket increased, i.e. it became economically more feasible, for increased district heating substitution prices and decreased electricity prices and taxes. This is in line with the recent reform of the taxes on heat recovery in Denmark, including a reduction of the related electricity tax from DKK 0,21 to DKK 0,008 pr kWh. Further, reduced temperatures resulted in increased heat recovery from the supermarket and increased savings compared to cooling only mode.


*Figure 4 Pictures from the heat recovery system and the outer facade of the Meny supermarket in Nordhavn*

It was also analyzed how the integration of an additional (external) evaporator influences the operation of the refrigeration plant. The refrigerant plant assessed was a two-stage transcritical $CO_2$ cycle as implemented in the Meny supermarket in Nordhavn. It was assumed that part of the gas cooler could be used as this additional evaporator. The aim of this additional analysis is to undergird the results of the aforementioned analysis by analyzing the consequences of heat recovery from a supermarket system using an additional evaporator for the plant and it's operation in more detailed using a thermodynamic model of the system. Two possible operation strategies of the additional evaporator were assessed. Firstly, the evaporator is operated at the MT evaporator pressure level. This would not require any changes in the compressor set-up. However, it may become necessary to reduce the MT evaporation pressure at ambient temperatures below the MT cabinet temperatures. Secondly, the evaporator is run at an individual pressure level. This means the evaporation pressure can be adapted optimally to the ambient air temperature. However, this would require that at least one of the high-stage compressors is reserved for the refrigerant flow from the additional evaporator and the gas bypass and thereby that it may be necessary to install an additional variable speed drive for one of the compressors. Both variants are depicted in the figure below.

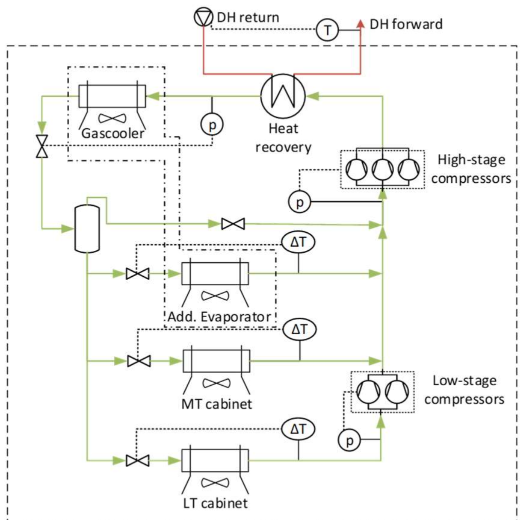



*Figure 5: Two possible variants of implementation of the additional evaporator, into the two-stage CO2 transcritical refrigeration cycle of the supermarket. Left: Additional evaporator is operated at the same pressure level as the MT cabinet. Right: The additional evaporator pressure level is independent of the MT pressure.*

The model was built in EES and was coupled to an optimization procedure. It was assessed how the gas cooler pressure set point and the load on the additional evaporator influence the thermodynamic performance of the system in terms of COP and exergy efficiency. In general the amount of heat that can be supplied to district heating may be increased by increasing the gascooler pressure or increasing the evaporator load. By increasing the gascooler pressure, the amount of heat that may be recovered above a certain district heating return temperature increases, while the evaporator load is unchanged and the required compression work increases.
The other option is to increase the refrigerant mass flow rate through the heat recovery heat exchanger. This may be achieved by adding an additional evaporator load, i.e. heat input at low temperatures into the system. This will however not change the specific heat recovery, only the absolute heat recovered. In order to evaluate the two possibilities, the limiting cost factors for an increase of heat recovery by means of increasing the gas cooler pressure or the additional evaporator load, was calculated.

In order to compare the economic performance three different heat recovery cases,
an hourly optimization was carried out for all three cases and compared to the performance of the cooling only base case. Here, it was assumed that the internal heat demand is always supplied by the heat recovery unit first, before heat is delivered into the LTDH grid. Further, no storage options for heating or cooling were considered. The gascooler pressure and load on the additional

evaporator (where applicable) were optimized such that the total operational cost, i.e. cost of electricity plus cost of buying district heating minus income from providing district heating, was minimized. The calculation was conducted using data from 2019 for electricity prices, district heating selling and purchasing prices and taxes and tariffs were assumed to be those of spring 2020. The annual results for all four cases, plus the optimal combination of operation strategy are shown in Table 1Table 2. The overall annual cost where found to be lowest for the optimal combination of strategies, followed by the heat recovery case with additional evaporator on MT evaporator pressure level (LTDH eva). The cost of heat recovery without additional evaporator (LTDH) and with additional evaporator in parallel (LTDH parallel eva) were similar and still almost 50 000 DKK/a smaller compared to the cooling only case, where the supermarkets internal heat demand was covered by purchased district heating. This saving in operational cost would be available to cover additional investment cost for heat recovery heat exchangers, equipment of the gascooler, such that parts of it may be used as evaporator and corresponding control systems.
The distribution of the different operation strategies in percentage of operation hours per year is represented in Figure 6Figure 9 and details regarding the performance of the different strategies may be found in Table 2Table 1. In the majority of the hours, heat recovery operation without additional evaporator is the cheapest operation strategy. This is in line with (Rørbæk Kruse and Abdikarim Ali, 2020), who found that heat recovery operation is economically feasible, especially due to the heat supplied internally and thus savings in the district heating purchasing cost. They also found that the additional cost of the extra evaporator limit the benefit of being able to supply more district heating. It may however be expected that the investment cost may be reduced when the existing gascooler could partly be used as evaporator.

*Table 12 Comparison of optimized operation of cooling only operation, heat recovery without additional evaporator, heat recovery with additional evaporator on MT pressure level, heat recovery with additional evaporator parallel to MT pressure level and the optimal combination of these.*

| | Amount of heating supplied in MWh | Amount of cooling supplied in MWh | Amount of electricity used in MWh | Total operational cost in kDKK |
|---|---|---|---|---|
| Cooling only | 0 | 844 | 64 | 271 |
| LTDH no Eva | 672 | 844 | 390 | 223 |
| LTDH Eva | 747 | 844 | 394 | 212 |
| LTDH parallel Eva | 706 | 844 | 399 | 222 |
| Opt. combination of operation strategies | 620 | 844 | 0 | 208 |

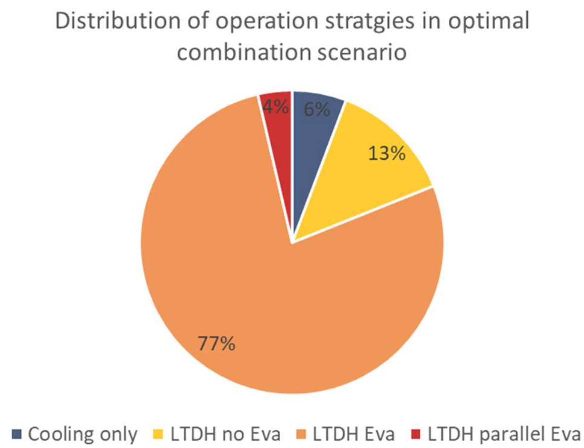



*Figure 6 Distribution of hours, where the different operation scenarios provide the lowest overall cost per hour.*

*Table 2~~1~~ Distribution of hours, where the different operation scenarios provide the lowest overall cost per hour, corresponding heating supplied, cooling supplied, electricity usage, average COP for cooling and COP for heating and average hourly operational cost.*

| | Recommended operation hours | Heat supplied | Cooling supplied | Electricity used | Average COP cooling | Average COP heating | Average cost per hour of operation |
|---|---|---|---|---|---|---|---|
| | h | MWh | MWh | MWh | | | DKK/h |
| Cooling only | 505 | | 49 | 12 | 4.02 | | 29.10 |
| LTDH no Eva | 1154 | 24 | 109 | 51 | 2.13 | 0.79 | 30.09 |
| LTDH Eva | 6787 | 586 | 657 | 301 | 2.18 | 4.33 | 22.25 |
| LTDH parallel Eva | 318 | 10 | 30 | 11 | 2.65 | 2.83 | 23.05 |

Finally, it should be explained how the two ways (increasing gas cooler pressure and increasing evaporator load) of increasing the district heating production behave in terms of operational cost. As explained above, this was assessed by looking at the limiting cost factor (LCF). As illustrated in Figure 7~~Figure 10~~, at low gascooler pressures it is always economically more feasible to increase the gascooler pressure in order to increase the heat production, as here the curvature of the isothermal lines can be exploited. At higher pressure the gain by increasing the gascooler pressure is less, then increasing the evaporator load becomes more feasible.

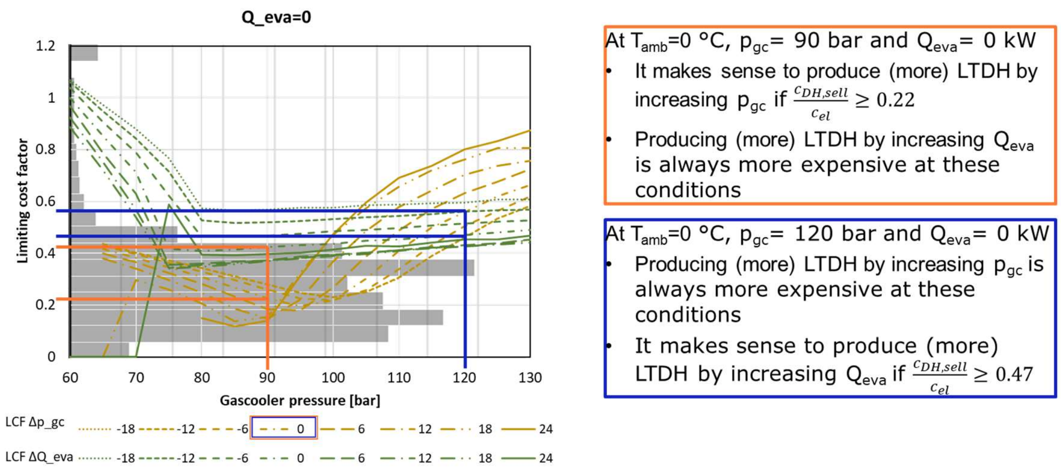



*Figure 7 LCF diagram for heat recovery set-up with parallel evaporator providing LTDH. The LCF is shown for an increase in gas cooler pressure (gold) and in evaporator load (green). The orange and yellow examples show how the diagram can be interpreted. The grey histogram in the background show the distribution of the actual ratios of* $c_{DH,sell}/c_{el}$ *in the year 2019 in Copenhagen, Denmark*

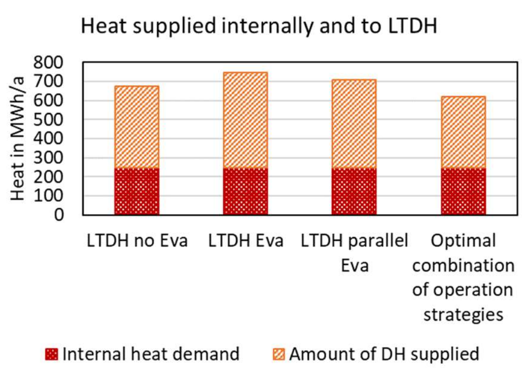



*Figure 8 Amount of heat supplied internally and to LTDH according to optimization results for 2019.*

Overall, it was found that heat recovery from supermarket refrigeration systems are economically and thermodynamically beneficial. If possible, the internal heat demand of the supermarket should be covered first by the recovered heat. The results further showed that there is a potential to recover between 371 MWh/a and 499 MWh/a LTDH in the different heat recovery cases, as also shown in Figure 8~~Figure 8~~. This is equivalent to a heating unit of 93 kW to 125 kW operating 4000 full load hours per year. If the legal framework allows and the local utility company is willing to buy district heating from decentral sources, this constitutes an additional income possibility for the supermarket owner. It further allows to better exploit the available plant capacity, which may be seen by the potential to increase the district heating production by employing an additional evaporator and the input power.

The demonstration was carried out through a control method for optimizing the heat production in the supermarket based on a PC running Matlab. The PC can access logged data from the DTU data server (DMS). The DTU/DMS system does not write access to the Danfoss controllers (to ensure separation of responsibility and security) and is hence only used a data logging system. The Danfoss controller can however be offset via the Danfoss cloud, hence the PC send offset commands to the Danfoss cloud that then offset the operation of the Danfoss controllers. An overview of the data communication is depicted below.

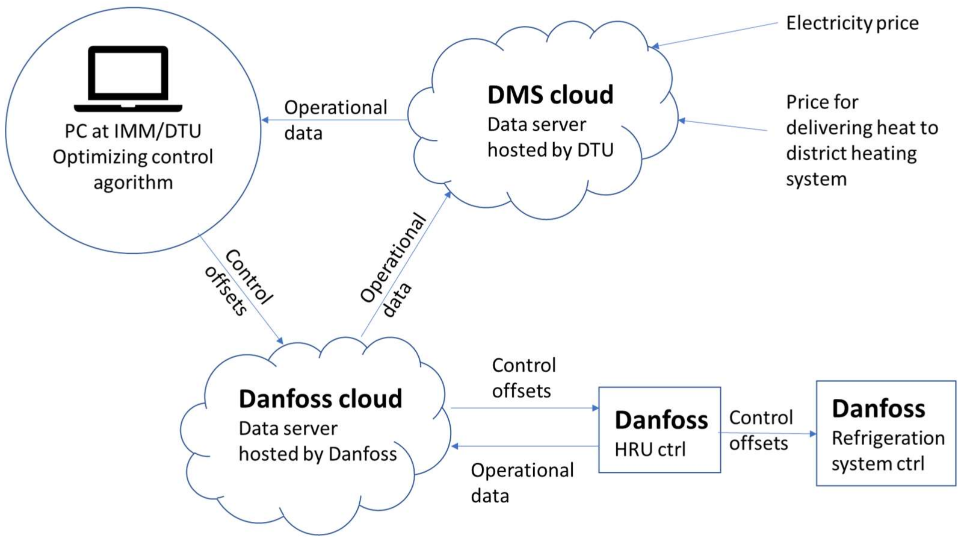



*Figure 9: Schematics of the communication setup for demonstrating the delivery of heat to the DH system.*

With the HRU installed in the supermarket and operational, it has been demonstrated that the communication to an external data acquisition is working and that it is possible to control the HRU remotely. It has further been demonstrated the HRU in fact can automatically produce hot water and deliver a surplus of heat to the district heating system.

An optimizing control method has been developed that automatically adjust the heat production in relation to the current electricity price and payment for the generated heat to the district heating system hereby maximizing the profit. Doing so by utilizing external signals representing the "state" of the DH and electric network.

It has finally been demonstrated that the unused compressor capacity can be activated to produce an increased amount of heat – currently due to lack of refrigerant charge it has not been possible to automatically run the refrigeration system in a mode where the spare compressor capacity is automatically activated.

### Dissemination related to task 10.3

- Rørbæk Kruse, J.C., Abdikarim Ali, Z., 2020. *Feasibility study of excess heat recovery from a supermarket to district heating*. B.Sc. Thesis, Technical University of Denmark, Department of Mechanical Engineering.
- Meesenburg, W. , Rørbæk Kruse, J.C., Abdikarim Ali, Z., Ommen, T., Thorsen, J.E., Elmegaard, B., 2020. *Flexible heat supply from supermarket refrigeration systems*. Presentation at Smart Energy Systems conference 2020, Aalborg.
- Chunjun Huang, Yi Zong, Shi You, Jan Eric Thorsen, Lars Finn Sloth Larsen, *A Cost-Driven Smart Heat Recovery Control for Supermarket Refrigeration System Coupled with District Heating System*, submitted for to the 4th International Conference on Smart Energy Systems and Technologies.
- B. Zühlsdorf, W. Meesenburg, T S Ommen, J E Thorsen, W B Markussen, B. Elmegaard. *Improving the performance of booster heat pumps using zeotropic mixtures*, Energy, 2018

- Rune Hermansen, Kevin Smith, Jan Eric Thorsen, Jiawei Wang, Yi Zong. *Model Predictive Control for a Heat Booster Substation in Ultra Low Temperature District Heating Systems.* 4th International Conference on Smart Energy.

**Bachelor projects**

- Knudsen, Rasmus Jelsbak. *Optimization of Operation of Supermarket Refrigeration System Integrated with District Heating, Optimering Af Drift Af Supermarkedskøleanlæg Integreret Med Fjernvarme*. 2019.
- Sahin, Celal Yunus. *Heat Recovery from Supermarket Refrigeration System to Low Termperature District Heating, Varmegenvinding Fra Supermarkedskøleanlæg Til Lavtemperatur Fjernvarme*. 2020.
- Kruse, Jens Christian Rørbæk, and Zakaria Abdikarim Ali. *Feasibility Study of Excess Heat Recovery from a Supermarket to District Heating, Feasibilitystudie Af Udnyttelse Af Overskudsvarme Fra Supermarked Til Fjernvarme*. 2020.

The project results were also discussed in a concluding meeting with the EUDP board on august 24, 2020.

## 6. Utilization of project results

### Heat Booster Substation (HBS) and Circulation Booster (CB), WP 10.1:

One important result is the field data gained during the project for the HRU and the CB. This data is the basis for evaluation of the concepts, but also the operation time itself gives an important indication of the durability of the compressor under the actual operation conditions. The opportunity has been used very actively to work in deep with the concept of the Heat Booster system. Several related MSc. And Bachelor projects where launched, in which the data is used for a range of technoeconomic analyses of various combinations of heat boosters, district heating architectures and possibilities on the electricity ancillary markets.
The Heat booster substation (HBS) does not see a commercial Danish market on the short term, due to analyses favorizing Low Temperature District Heating (LTDH) over Ultra Low Temperature District Heating (ULTDH) under the Danish framework conditions. On some international markets, however, the concept is commercially interesting. Markets exist due to other framework conditions and business models.
The circulation booster (CB) is expected to find a market in DK in 2-4 years, especially in combination with heat networks supplied by large central heat pumps the direct payback time is short, less than 3 years. At current tariff structures, and based on the case I Strandboulevarden, the direct payback time is calculated to 5 years. The concept has not been explicitly investigated with regards to international markets, but a simple calculation tool is made, and by a few parameters such as electric price, district heating price and return temperature bonus the simple payback time can be estimated.

### Remote controlled valves for regulation of a water based building space heating. (WP 10.2):

The results from the project have been implemented in the Danfoss Ally product line. Through the open partner API's, it will become significantly easier for district heating utilities to use the systems to unlock heating flexibility.

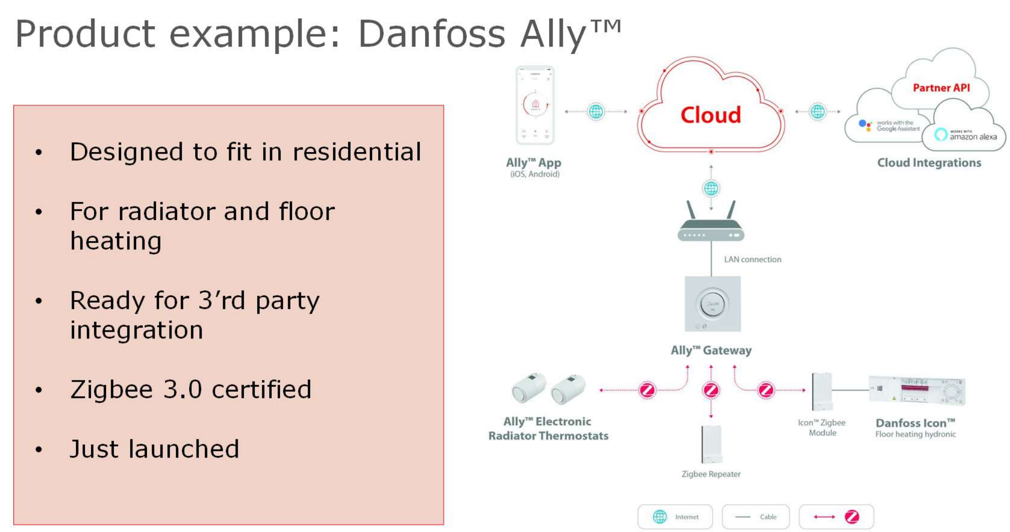



*Figure 10: Danfoss Ally architecture.*

Futhermore the progress in the project and the increased focus on flexibility and hydronic balancing has supported and contributed to inform Danfoss' acquisition of the Finnish company LeanHeat and choice to expand Danfoss' expertise in the field of AI based control of district heating systems.

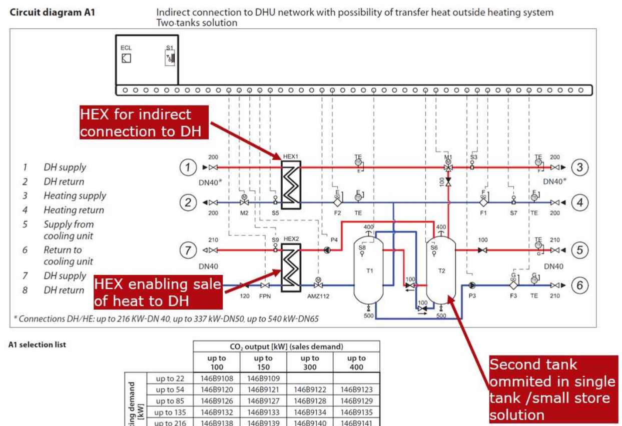
DTU Byg hopes to pursue this concept in further research with Danfoss as well as further development of digital tools for improved maintenance of heating systems. These findings all support that there are a number of local advantages to be had, which may justify the cost of the home automation systems and the infra-structure around them. The offering of flexibility to the heat network thus becomes less dependent on a quantitative valuation of the flexibility service.

**Utilization of excess heat and spare heat pump capacity, WP 10.3:**
The design and preliminary test results has feed into an analysis of the economic feasibility of the supermarket delivering waste heat to the DH. In this several Danfoss units have contributed to the development of the business case, in which different strategies and models for providing and receiving payment has been investigated. This revealed that for the agreed payment model towards HOFOR, the supermarket MENY in Nordhavn can generate a profit of 86.000 DDK/year yielding a payback time of the installation of 3-4 years. In case a so-called "netto" arrangement is applied the profit would be significantly higher.

The Heat Recovery Unit (HRU) has already been introduced as a product in combination with CO2 based compressor systems. Since the initiation of this project Danfoss has worked to standardize a portfolio of products to the Food Retailer end use market. As a result, Danfoss has already created 180 new SKU's with variants that include direct and indirect coupling to the district energy grid, with and without sales to the grid, and with single and dual tank versions. The various configurations come in a range of sizes to suit the needs from small stores to hypermarkets.

180 code numbers split on 6 variants with different capacities:

- A1: Indirect connection to district heating two tank solution with heat sales
- A2: Indirect connection to district heating two tank solution <u>without heat sales</u>
- A3: Direct connection to district heating two tank solution with heat sales
- A4: Direct connection to district heating two tank solution <u>without heat sales</u>
- A5: special versions, 4 codes
- A6: Indirect connection to district heating single tank solution <u>without heat sales</u>
- A7: Direct connection to district heating single tank solution <u>without heat sales</u>




A1 selection list

| Heating demand [kW] | CO₂ output [kW] (sales demand): up to 100 | up to 150 | up to 300 | up to 400 |
|---|---|---|---|---|
| up to 22 | 146B9108 | 146B9109 | | |
| up to 54 | 146B9120 | 146B9121 | 146B9122 | 146B9123 |
| up to 85 | 146B9126 | 146B9127 | 146B9128 | 146B9129 |
| up to 135 | 146B9132 | 146B9133 | 146B9134 | 146B9135 |
| up to 216 | 146B9138 | 146B9139 | 146B9140 | 146B9141 |
| up to 337 | 146B9144 | 146B9145 | 146B9146 | 146B9147 |
| up to 540 | 146B9150 | 146B9151 | 146B9152 | 146B9153 |

*Figure 11 Danfoss DEN Portfolio of Heat Recovery Units*

The marketing has started as a collaborative effort between Danfoss heating and cooling segments[1]. The product was first presented at Euroshop exhibition in 2017, and has since been a standard element in the Danfoss Smart-store portfolio. Marketing materials have been prepared and shared broadly, including technical leaflets, product sales presentations, along with videos and other items for sharing on the Danfoss website and on social media. A recent video presents the story of a customer that has decided to install an HRU in all stores (Figure 13~~Figure 13~~.) Danfoss has since the launch produced and sold more than 100 units to retailers in Norway, Denmark, Sweden, Finland, Lithuania and Germany.

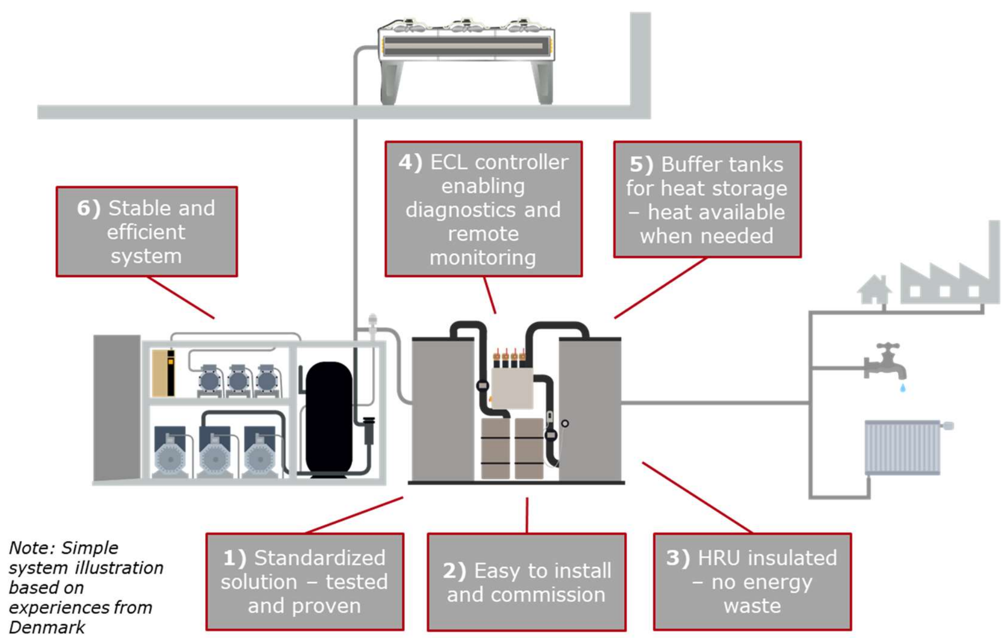



*Figure 12 Elements of the Danfoss HRU value proposition*

[1] This two business segments have recently been joined into one: "Danfoss Climate Solutions"

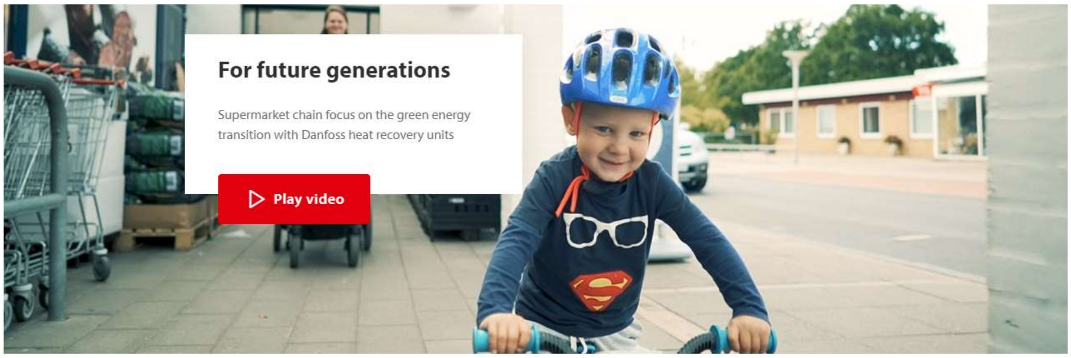



*Figure 13 Click on the image to go to a Danfoss branding film featuring the HRU*

An assessment of the market opportunity has been made based on the number of $CO_2$ refrigeration systems historically and expected sold in the EMA region (Figure 14~~Figure 12~~.) While all stores will require heat for hot tap water, the space heating demand varies based on size of store and with climate according to the European Heating index (+/-20%). Moreover, it needs to consider that not all stores are in a district heating area, hence, will not be able to improve the ROI with sale of excess heat to the grid. Given these variances and the general acceptance of only short ROI's of less than 2-4 years, the addressable market volume for heat recovery is expected to be roughly half that of the $CO_2$ sytems. This yields a direct addressable market value of 45m€ in 2020 with substantial growth rate.

Based on the size of the opportunity, Danfoss has recently opened a new position for a global HRU application champion to support Danfoss sales in onboarding new customers as well as provide inputs to product improvements.

The Danish market is unique in that there is a high penetration of $CO_2$ systems coupled with the highest proportion of homes serviced by district heating globally. At the start of this project the proposition for the retailer to recover and export excess heat was less attractive. Lack of clarity on how the retailer would be taxed for various operating modes as well as rules requiring accounting and not allowing to profit from the sale of heat, made it difficult to propogate the technology. Attention generated by this project and the Super Supermarkets project have helped to resolve these barriers at the legislative level. A supportive legal and tax environment in the home market will help to mature the technology for export.

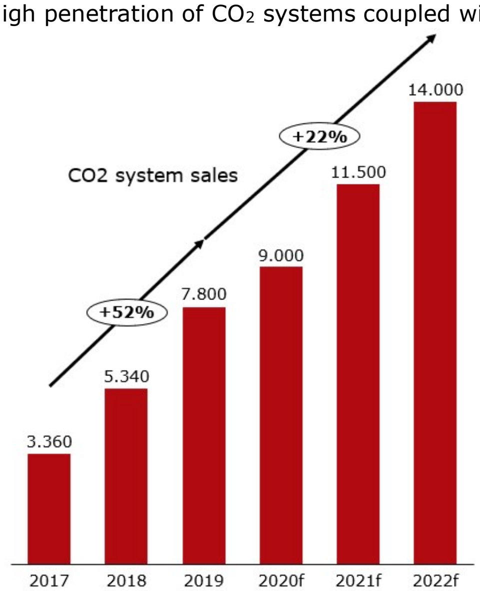



*Figure 14 Historical, and forecasted $CO_2$ refrigeration system sales in the EMA region as primary basis for calculating the addressable market.*

To further mature the markets to the technology, large scale rollouts of the technology are essential. In the Netherlands, thereis potential to scale the solution through the Warmtelinq program. Within the supply area of HOFOR, the solution will be relevant for up to 450 supermarkets with an aggregated heat supply of 50 MW, while at the same time offering 10 MW flexible electricity consumption. High carbon intensity district heating grids, for example Ålborg or Viborg, can reduce intensity significantly with similar rollouts. Large collaborative projects as these are essential to scale the business and will translate into larger market shares, also on export markets.

Today solutions are implemented in the products (supermarkets control systems and the heating control system) that already now enables the possibility to utilize excess heat for either delivering to the district heating system or for building heating. The products also support the use of spare compressor capacity for providing extra heat. With the recent change In Danish legislation it is expected to become a standard solution in the coming 1-2 years. These solutions are expected to follow the adaptation of CO2 (natural refrigerant) for supermarkets refrigeration which today is a common solution in North Europe – expected to increasingly spread globally during the coming 3-4 years – following the legislative requirements for use low GWP (Global Warming Potential) refrigerants.
Danfoss has plans to develop the product for export markets. Subsequent to rollout on the Danish market, Danfoss expects to focus on other Nordic markets as the next step followed by Eastern Europe, Central Europe, and finally the remaining global markets. As such, following the growth of $CO_2$ refrigeration as it spreads globally. The product will be adapted to the local markets as necessary and will be augmented with additional monitoring, management and optimization services. The ambition is that the systems will be able to support complex grid services such as demand side management of both the electrical and thermal grids.

**Recommendations made**

In the project we have chosen to summarize the learnings into a set of specific recommendations, integrated with the main EnergyLab Nordhavn project and published in October 2019. Specifically related to the demonstrations under this grant are the following.

- 2. DISTRICT HEATING COMPANIES CAN APPLY A PRICE DIFFERENCE BETWEEN NORMAL DISTRICT HEATING AND LOW-VALUE DISTRICT HEATING TO INCREASE THE INTEGRATION OF SURPLUS HEAT.
  The basis for utilizing low-value heat (surplus heat at low temperatures) in the district heating grid can be the design and expansion of ultra-low temperature district heating clusters connected to existing grids. This will also enable the use of return water from existing district heating for ultra-low temperature clusters, which will result in lower heat losses from the pipes and better operating finances on the plants.
- 4. THE ENERGY FRAMEWORK CALCULATION PROGRAMMES, I.E. THE BE PROGRAMMES (CURRENTLY BE18) OF THE SBI (DANISH BUILDING RESEARCH INSTITUTE) MUST BE ADJUSTED.
  The current rules are poorly suited for hybrid solutions, which prevents the implementation of some of the smart energy solutions such as a combined use of district heating and electricity for the production of hot water. The calculations only take into account the grounds until the boundary line, which means that the benefit of a lower heat loss from the distribution of heating to homes with low-temperatures or ultra-low temperatures is not included.6
- 5. CURRENT BUILDING ENERGY LABELS SHOULD BE UPDATED.
  The current labels for building energy consumption assume that the behaviour of the residents is rational and, not least, that the construction is perfect, and that the technical installations are designed and aligned with each other. This does not provide a true and fair view of the energy consumption in buildings and we therefore recommend supplementing the current labels with a measured and realized energy label which is in line with reality. We have shown how home automation systems can detect heating and ventilation systems that are poorly aligned with each other early. They thus provide a database that makes it meaningful and reasonable to provide clients, developers, and consulting engineers the responsibility of documenting and verifying that the building actually delivers as promised over a number of years.
- 9. ENERGY SAVINGS SHOULD BE SUPPORTED BY SMART BUILDINGS WHICH SHOULD BE INCLUDED IN THE EARLY URBAN DEVELOPMENT PLANNING STAGE. DGNB and other certification systems are prepared for the use of smart building management, as it is deemed

to help reduce energy use. The latest edition of EU's EPBD (Energy Performance of Buildings Directive of 2018) now also includes requirements for building automation and control systems, but so far only for large commercial buildings (with heating systems with an output of at least 290 kW). Similar requirements should also be made for housing construction and small-scale buildings integrated into city energy systems. The opportunities in smart buildings, energy, and solutions in connection with urban development require all relevant partners to be involved early in the process. In some cases, the project has played a facilitating role that municipal administrations and urban development companies can play in some cases by making explicit demands for contractors to establish these functions in the buildings, including housing construction.

- 11. BETTER POSSIBILITIES FOR ACTIVATING HEAT FLEXIBILITY SHOULD BE INTRODUCED SO THAT FLEXIBILITY CAN CONTRIBUTE MORE TO THE INTEGRATION OF THE ELECTRICITY AND HEATING SYSTEMS.
  The need for energy flexibility is expected to increase in future energy systems. The need for flexibility arises due to fluctuations in energy production from renewable energy and, in part, the energy consumption of new technologies, as production and consumption must be balanced and bottleneck issues handled. Here, sector coupling is key, and more flexibility solutions and products that can increase the integration of renewable energy into the system in the best and cheapest way need to be arranged. There is already an emerging market for electricity flexibility services. An increased market for heat flexibility, where it can be quantified, demanded and supplied under market conditions, will provide a diversity of solutions and stimulate innovation in solutions, especially in relation to the connection between electricity and heat. This could also include dynamic heating tariffs.
- 19. SMART BUILDING MANAGEMENT MUST BE INCORPORATED INTO NEW CONSTRUCTION WORKS.
  Smart home technology can be incorporated into both new construction work and renovation work, and home automation must be integrated into the design. It provides a range of comfort benefits while allowing energy consumption to be coordinated with energy supply, e.g. so that the peak load in total district heat consumption can be levelled and thus contribute to reducing the use of fossil fuels for peak-load plants.15 EU's Energy Performance of Building Directive (EPBD) already includes increased requirements for automation and control systems in commercial construction. Based on the project work, we propose to include housing construction, more benchmarks16, and performance guarantees in the legislation. We also propose that more players be involved in the preparation of the legislation.
- 20. MEASUREMENT AND CONTROL SYSTEMS SHOULD BE DESIGNED FOR INTEROPERABILITY.
  IoT, like with energy meters, has an infrastructure where you can become tied to certain supply chains. By making demands for interoperability, the state of the energy system can more easily be made available to several players, and it is possible to present a project to the contractor with a reduced risk of being tied to a particular supplier during the operational phase. In the project, we have learned how difficult it can be for third party players to offer solutions and services based on data streams that are beyond their control.
- 22. CONTRIBUTION TO THE SPECIFICATION OF THE NEW REGULATORY TESTING ZONES.
  There is a political focus on the creation of these test zones, and using our experience from Nordhavn to qualify the work with these would be an obvious next step. Here, advisers have an opportunity and a key role in bringing knowledge of the barriers of technological distribution into play, along with university recognition. Furthermore, it would be an obvious choice to designate Nordhavn as the regulatory test zone based on investments made, total players involved, and experience accumulated. A complementary option is using the existing free municipality scheme.
- 25. INCREASED VALUE IS AVAILABLE FOR PLAYERS WHO CAN TRANSLATE KNOWLEDGE OF CONSUMPTION PATTERNS INTO SYSTEM SERVICES.

If you know your customers well and have a high diversity, you as an aggregator can make sure that, e.g., the storage solutions are pushing consumption at times when power is greenest, and at the same time offer services to energy companies such as frequency stabilization, voltage quality stabilization, or peak shaving.

## 7. Project conclusion and perspective

The project has aimed to support the transformation of the energy system to a reliable, cost-effective and sustainable system based on renewable energy through the development of intelligent energy solutions based on innovative technology, new operational and commercial approaches. The experimental activities with integrated research-based technology development set out to create substantial *commercial impact* by leading the way for new innovative products, attract new energy businesses to Denmark and create knowledge based jobs, *societal impact* by developing a future energy system, guide new rules and regulation, emerge new market designs and *scientific impact* by new knowledge breakthroughs and expansion of the Danish knowledge-base.

Towards this purpose, the project has yielded a number of results, including the following specific demonstrations

- We have demonstrated how district heating at ultra-low temperatures combined with a booster heat pump can supply housing blocks (buildings) with hot water as well as ensure a low return temperature.
- We have demonstrated how the varying energy needs of buildings can be exploited when coordinated by a district heating company enabling energy efficiency improvements and a reduction in the use of peak load boilers.  This heating flexibility has also been demonstrated through the use of home automation systems. This will help realize a district heating system being 100 % CO2-neutral thereby contribute to realizing the Copenhagen 2025 climate plan for district heating.
- We have shown how heat from supermarket cooling equipment can be exported to the district heating network, and due to the nature of the CO2 based technology, this heat export can be controlled so that the systems contribute as decentral peak load capacity for the district heating utility, reducing the need for fossil fuelled peak load boilers.
- We have made available a range of data streams and data series on the energy data warehouse that supports secure real-time data sharing between the stakeholders, thus supporting the realization of a smart energy system encompassing electricity, heat, buildings, transport, and residents. The ability of the system to support real control applications has also been demonstrated.
- Together with other EnergyLab Nordhavn demonstration activities and a shared showroom the demonstrations constitute a living lab and Energy Hub, combining communication, stakeholder dialogue, international marketing, incubation, and innovation. This platform has enabled us to spread awareness of Danish energy technology to several national and international delegations.  If continued backing to the ecosystem can be established, this setup has a great potential to support the acceleration of sustainable energy solutions in DK and the creation of international export opportunities.

In Denmark, the most readily applicable results are the circulation heat boosters, the activation of flexibility in the built environment using the Danfoss Ally platform, the roll-out of heat recovery solutions in supermarkets and exploitation of these solutions to reduce the need for fossil fired peak load boilers and pave the way for lowering the temperatures in the district heating networks, in Copenhagen as well as in other networks in DK and abroad.  The heat booster substation solution is expected to find a market outside Denmark first.

As main industrial partner, Danfoss has benefited greatly from the project. It has demonstrated how the Danfoss solutions play a role in a sector coupled energy system, and fulfilled the ambition as a lighthouse project.  Generally speaking the project has contributed with valuable insights in smart energy systems and sector coupling, and especially the complex theme on district heating units, booster heat pumps and use of excess heat sources are of great international interest.

## 8. Annex, Overview of dissemination

Reports, PhD dissertations, articles etc will be added to the continuing list on www.energylab-nordhavn.dk. Apart from the articles and other references made in section 5 regarding the specific demonstrations, in the following a selection of general interest is listed, many of these are integrated with the main EnergyLab Nordhavn Project (grant 64014-0555):

### Recommendations and Main results

Recommendations and main results, October 2019 (UK)
Anbefalinger og hovedresultater, oktober 2019 (DK)

### Project presentation videos

Results summary video, October 2019
Introducing EnergyLab Nordhavn, summer 2018
Sustainable heating in cities, summer 2018
Circulation Boosters - Presentation with Voicetrack

Also integrated with the main project, the project has also made it to a number of national and international mainstream media. A few examples (Circulation in brackets where known/relevant):

| | | |
|---|---|---|
| 15-11-2015 | Jyllandsposten (98.000) | Fremtiden er sammentænkte energiløsninger |
| 28-12-2015 | Jyllandsposten (98.000) | Der er arbejdspladser i grønne ambitioner |
| 15-05-2016 | Liberation, France (140.000) | Copenhague se rêve vierge de carbone |
| 22-mar-17 | Politiken (98.000) | Nordhavns grønne energi tiltrækker borgmestre fra hele verden |
| 30-aug-17 | Børsen (60.000) | Energikilderne kan udnyttes mere intelligent |
| 13-Sep-18 | tv2Lorry.dk | København skal vise sig frem som vært på klimatopmøde |
| 21-May-19 | weforum.org | This is how Copenhagen plans to go carbon-neutral by 2025 |
| 10-Aug-19 | NTV – Tyskland | Wie Kopenhagen klimaneutral werden will |
| 27-Aug-19 | Politico.eu | Cyberthreats could turn smart cities into dumb ones |
| 20-Oct-19 | RTP, Portugal TV | Copenhaga, a capital que quer ser neutra em emissões poluentes |
| 06-12-2019 | El Tiempo, Colombia (1.1 Million) | Nordhavn, la ciudad inteligente basada en energía renovable |
| 24-06-2020 | Berlingske Smart Cities Tillæg | Smart energiforbrug i fremtidens smarte by |

### Deliverables

D10.1a: Prototype realisation of Heat Booster substation
D10.1b: Heat Booster substation realisation for field test and installation in buildings
D10.1c: [Report (public)] Heat boosters for hot tap water and heating
D10.2a: Prototype realisation of adapted Living By Danfoss Controller
D10.2b: Danfoss Living controller realisation for field test and installation in buildings
D10.2c: [Report (public)] Smart control of water based building heating services
D10.3a: Control Concept Development
D10.3b: Test Concept in Field
D10.3c: [Report (Public)] Smart utilisation of spare heat pump capacities (To be published after project completion)