Deliverable no. 5.4a:
Optimizing temperatures in low-temperature district heating networks

Photo: By & Havn / Ole Malling

HOFOR
Author, Jeppe Krogh Skjølstrup
Date April, 9th, 2019]

Public deliverable ☒
Confidential deliverable ☐

Preface

EnergyLab Nordhavn – New Urban Energy Infrastructures is an exciting project which will continue until the year of 2019. The project will use Copenhagen's Nordhavn as a full-scale smart city energy lab, which main purpose is to do research and to develop and demonstrate future energy solutions of renewable energy.
The goal is to identify the most cost-effective smart energy system, which can contribute to the major climate challenges the world are facing.

Budget: The project has a total budget of DKK 143 m (€ 19 m), of this DKK84 m (€ 11 m) funded in two rounds by the Danish Energy Technology Development and Demonstration Programme (EUDP).

Forord

EnergyLab Nordhavn er et spændende projekt der løber til og med 2019. Projektet vil foregå i Københavns Nordhavn, og vil fungere som et fuldskala storbylaboratorium, der skal undersøge, udvikle og demonstrerer løsninger for fremtidens energisystem.
Målet er at finde fremtidens mest omkostningseffektive energisystem, der desuden kan bidrage til en løsning på de store klimaudfordringer verden står overfor nu og i fremtiden.

Budget: Projektets totale budget er DKK 143 mio. (EUR 19 mio.), hvoraf DKK 84 mio. (EUR 11 mio.) er blevet finansieret af Energiteknologisk Udviklings- og Demonstrationsprogram, EUDP.

Project Information

Deliverable no.: D5.4a
Deliverable title: Optimizing temperatures in low-temperature district heating networks
WP title: District heating infrastructure
Task Leader: Jeppe Krogh Skjølstrup
WP Leader: Kristian Honoré
Comment Period: April 9th , 2019 – April 26th, 2019

For further information on this specific deliverable, please contact:

Jeppe K. Skjølstrup, jksk@hofor.dk
Kristian Honoré, krih@hofor.dk

For other information regarding EnergyLab Nordhavn, please contact:

EnergyLab Nordhavn Secretariat
Center for Electric Power and Energy, DTU Electrical Engineering
Elektrovej
Building 325
DK-2800 Kgs. Lyngby
Denmark

E-mail eln@dtu.dk
Tlf. +45 45 25 35 54

www.energylabnordhavn.dk

Table of Contents

List of Abbreviations

4GDH:	4th generation district heating
BHP:	Heat Booster Substation
DH:	District heating
DHW:	Domestic hot water
HP:	Heat pump
IHEU:	Instantaneous heat exchanger units
LTDH:	Low temperature district heating
ULTDH	Ultra low temperature district heating

1 Executive Summary

This project investigates the case of implementing lower DH operating temperature in the district of Nordhavn consisting of two existing subareas of Århusgadekvarteret and Sundmolen, plus the future subarea of Levantkaj.

These areas consist of mostly new buildings fulfilling the requirements of the energy label; A2015, which means that buildings theoretically consume a maximum of 30 [kWh/m2] $+ \frac{1000\ [\text{kWh}]}{\text{heated floor area [m2]}}$ per year. The investigation consists of three independent analyses.

The first is a practical test and analysis of the supply of low temperature district heating in four buildings located in Nordhavn.

The second is a business economic analysis of heating supply options for Nordhavn.

The last analysis considers the business economic costs of expanding the DH grid in the subarea of Levantkaj in Nordhavn.

The business-economic costs are defined as the costs, which the DH Company would have by investing and operating the technologies. These include current tax, tariffs and investment cost, and market price projections of buying heat and electricity by the reference year of 2035.

The four buildings reflect the building stock of Nordhavn, being three new multifamily houses from 2015 and 2017, built according to the energy consumption restriction in the building code of low-energy class: A2015. The last building is one old commercial building from 1955, built before the implementation of building codes. Consequently, no restrictions on energy consumption has been put in the construction of this building. All buildings were tested with supply temperatures ranging from 40-70°C.

The business economic analysis investigates the scenarios of

1st A reference scenario with collective grid connection at operating temperatures of 70/40°C
2nd A LTDH scenario with collective grid connection at operating temperatures of 60/35°C, combined

with decentral heat production by a seawater HP located in Nordhavn
3rd A ULTDH scenario in which Nordhavn has no collective grid connection, but has base-load heat supply from a seawater HP, back-up/peak load production from an electric boiler, a thermal storage as well as local DHW production by a booster HP connected to the DH return pipe.
4rd A ULTDH scenario identical with scenario 3, but with local DHW production from electric boilers.

The grid expansion analysis of Levantkaj also investigates the influence on the heat price by applying design temperatures at -12°C, -3.5°C and 5.5°C. The design temperature determines the grid capacity, because if a low design temperature is chosen, then it implies a large heat demand and consequently a large grid capacity and vice versa when a high design temperature is chosen. When a high design temperature is selected, the lack of grid capacity is compensated through elevated supply temperatures. The maximum supply temperature is considered to be 90°C for a distribution grid supplied by a sea water HP.

Results of the analyses reveals that technical improvements are needed on building level before LTDH at 60°C/35°C can be realized, whereas even more improvements are needed to realize ULTDH of 40/25°C. Problems are associated with heating installation, substation design and control systems. Business economic results reveal LTDH supplied by a sea water HP (scenario 2) is the most attractive. Grid expansion in Levantkaj at -3.5°C design temperature seems to improve the overall business case of all scenarios compared to a design temperature of -12°C, despite periodically increased supply temperatures that cause a reduced COP of the HPs.

It is recommended to improve the operation of the building's heating systems in Nordhavn to harvest the benefits of a possible future LTDH supply.

Version Control

Version	Date	Author	Description of Changes
[Official versions only]	[yyyy-mm-dd]		
1	05-02-2019	Jeppe Skjølstrup	Draft
2	18-02-2019	Kristian Honoré	Review
3	11-03-2019	Jan Eric Thorsen	Review
4	18-03-2019	Jeppe Skjølstrup	Revision
5	22-03-2019	Kristian Honoré	Update for ext. review
6	01-04-2019	Svend Svendsen	External review
7	09-04-2019	Jeppe Skjølstrup + Kristian Honoré	Update for approval in WPL group

Quality Assurance

Author	Reviewer	Approver
Jeppe K. Skjølstrup	Svend Svendsen / DTU-BYG	WPL group

Status of deliverable		
Action	**By**	**Date/Initials**
Sent for review	Kristian Honoré / HOFOR	**25-03-19/krih**
Reviewed	Svend Svendsen / DTU-BYG	**01-04-19/SvSv**
Verified	Kristian Honoré / HOFOR	**09-04-19/krih**
Approved	WPL group	**26-04-19/WPL**

2 Background

Denmark is in the transition towards a CO_2 neutral society 2050. It involves the implementation of fluctuating renewable energy sources and thus, the need for more flexibility in the energy system to ensure security of supply to meet the demand. The steps towards a 100 % renewable energy system takes place on various levels and in different regions of Denmark.

In the Greater Copenhagen, goals are to speed up the transition process. Hence, Copenhagen municipality has since 2009 had a vision to become CO_2-neutral within 2025 (Copenhagen Municipality 2009).

The transition process requires responsibility and action of various actors. It includes also the DH and utility company of Copenhagen, HOFOR. The DH Company serves 600.000 inhabitants covering 99 % of the heat demand in Copenhagen. By 2025 the heat production need to be CO_2-neutral.

2.1 The role of low temperature district heating

Reducing CO_2-emissions in the DH sector may take the form of either

- introducing renewable production units
- reducing heat demand
- introducing more flexibility

Reducing DH operating temperatures falls into all three categories. Hence, reduced return temperatures increase the efficiency of the CHP plants' condensing units and ensures the need for less pump power. Lower DH operating temperatures, drastically improves the COP of heat pumps (HP) and increases the efficiency of solar thermal plants. It also allows for the utilization of more excess heat sources. Presumably, more HPs will be implemented, which again allows for more integration of fluctuating renewable electricity production as the HPs allows electricity to be stored as heat in hours of excess electricity production. Lastly, heat losses in the DH system are reduced because the temperature difference between the ground and temperatures in the pipes are reduced. (Lund et. al 2018)

2.2 Limits to lower DH operating temperatures

Whereas above mentioned benefits are desired, technical challenges on grid and costumer level might hamper the reduction of temperatures.

Forward-looking design guidelines of building installations have through time increasingly pushed for lower operating temperatures, by ensuring an improved insulation standard and heating installation. Consequently, the largest potential of lowering DH operating temperatures are deemed to be in new areas, as buildings fulfill up to date heating installation requirements. (DTCHA 2018)

However, building heating systems do not always operate as intended. From an interview with 56 Swedish DH companies Månsson 2018; identified faults causing under-performance of substations that hampers the implementation of lower DH operating temperatures in substation. The more typical being leakages, customer s' internal heating system and malfunctioning control valves. (Månsson 2018)

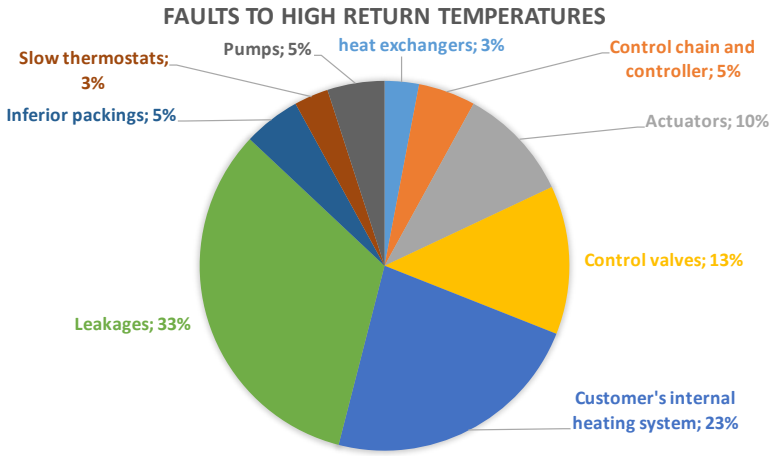


Figure 1: Typical faults identified in 56 Sweedish substations (Månsson 2018)

On a distribution grid level, lower DH operating temperatures result in reduced capacity of existing grids, because the cooling in each building will be lower the more supply temperatures are reduced. Malfunctioning substation reinforce capacity needs, and if the pump capacity is limited or the pipes' hydraulic load exceeds the pressure threshold, new investments in grid infrastructure might be needed. Thereby, technical limits in the distribution grid might lead to high economic costs, when implementing lower DH operating temperatures. It underlines the importance of ensuring lower DH temperatures by more efficiently designed and operated substations, because it will free up more hydronic capacity in the grid.

2.3 Reducing DH temperatures in Nordhavn

Nordhavn is a new district in Copenhagen located by the seaside. The district is presumably fully developed by 2050, but DH already supplies the built subareas of Århusgade and Sundmolen. This report considers 2035 as the reference year, where Levantkaj would be added to the DH supply area. Thus, the district of Nordhavn considered in this report, appear as of figure 2.

The district consist of only a few older buildings, preserved for aesthetic reasons, e.g. (Copenhagen Municipality 2015). Most buildings are/will be built according to the requirements of A2015 or newer. As a matter of fact, the heating installations of buildings in Nordhavn are designed for a maximum supply at 60 °C and a maximum return temperature of 40°C and 30°C from the heating and DHW circuit, respectively (construction support, 2018) . These design temperatures are well below HOFOR's operating temperatures, which range from 65-95°C. Therefore, HOFOR believes that LTDH in Nordhavn at 60°C-70°C would be technically possible in the most hours of the year. However, to realize these temperatures, Nordhavn needs to be separated from the neighboring distribution grids as the building mass of these districts require up to 95°C in the heating season. Implementing grid separation to harvest temperature reductions at 25-35°C requires the proof of a positive business case.

Though, the conditions for lower DH operating temperatures are ideal, technical challenges as of section 1.2 might still be an issue. Hence, also new buildings' substation can be operated inefficient or designed poorly, which can hamper the introduction of lower DH operating temperatures. Likewise,

the subarea of Levantkaj needs a grid to allow DH supply, it leaves a potential to consider how the design of the grid can be prepared for lower DH operating temperature, while at the same time not being too costly.

To present a holistic picture on the challenges and benefits of lower DH operating temperatures in Nordhavn, this report investigates the building heating system, production and grid levels in Nordhavn. On the building heating system level, four buildings located in Nordhavn are tested at lower DH operating temperatures. These are one older commercial buildings and three new multifamily houses. The performance of the buildings are evaluated based on the delivered cooling at each supply temperature. On production level, 4 heating supply scenarios are considered. The scenarios includes local production units, and operating temperatures ranging from 40-70°C. The scenarios are evaluated based on the business economic costs.
On grid level, different design criteria are evaluated with purpose of identifying the most feasible design criteria from a business economic perspective.

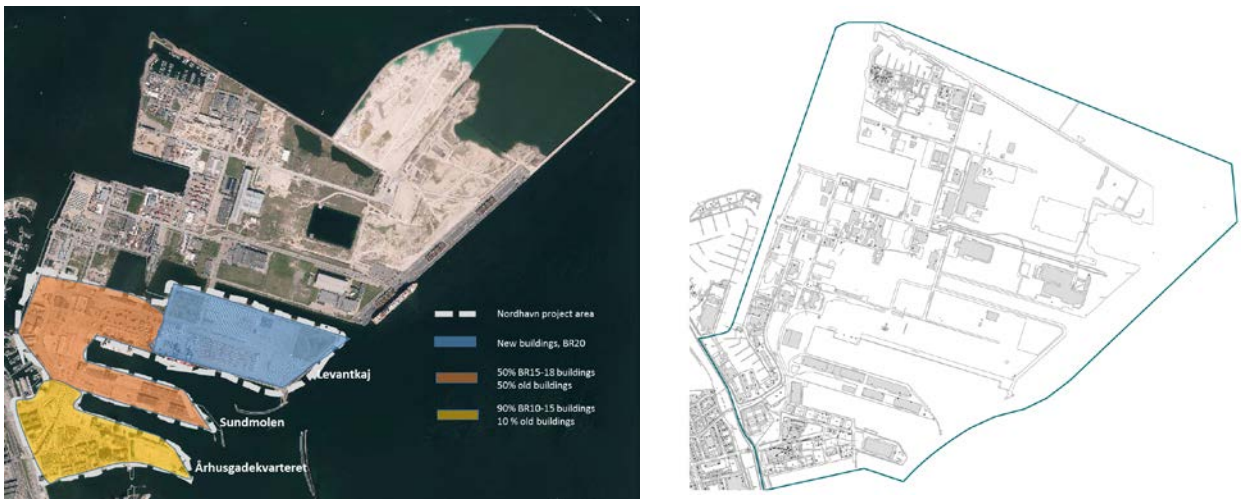


Figure 2: The picture on the left hand, visualizes the area of Nordhavn which is considered in this report, while the right hand visualizes the entire low-temperature area of Nordhavn in which maximum supply temperatures of 70°C are intended (Own figure) Data: (HOFOR 2018).

3 Building heating system analysis

In this chapter, the four demonstration buildings in Nordhavn will be presented in terms of building design and installation, energy consumption and return temperatures. Afterwards, the reader is presented to the test program together with the cooling-evaluation-method of the demonstration buildings. Lastly, results are presented, concluding how prepared the buildings are for lower supply temperatures.

Building design and installation

All data regarding building design and heating installations of each of the four buildings is presented in Table 1

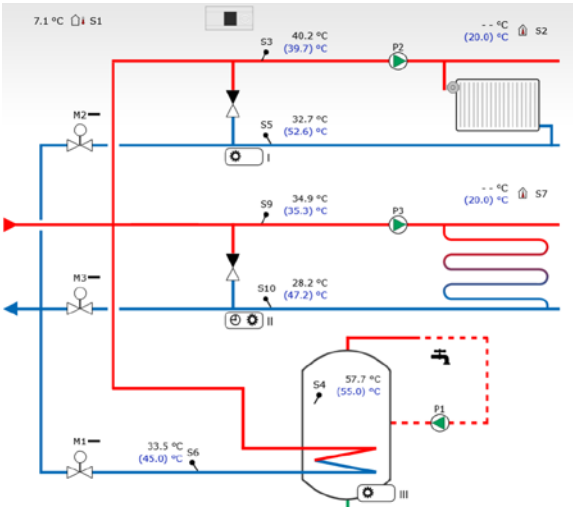
Table 1: Building design and heating installation of test buildings

Building data	Building 1	Building 2	Building 3	Building 4
Building [year]	2015	2015	2017	1955
Heated floor area [m2]	4124	2679	7008	7066
DHW share of total consumption [%] [1]	23%	33%	21%	4%
Building type	Multifamily+small commercial area	Multifamily+small commercial area	Multifamily+small commercial area	Commercial+ storage facility
Apartments	28	22	72	None
Apartments per floor	4.7	3.7	12	None
Heating system in apartments/ commercial areas	Floor heating + ventilation	Floor heating	Floor heating	Radiator[2] (located in the ceiling)
Heating systems common areas	Double-looped radiator circuit	Double-looped radiator circuit	Double-looped radiator circuit	Single-looped radiator circuit
Design temperature of heat exchanger[C°]	60-40°C	60-40°C	60-40°C	70/40°C
Ventilation commercial area	Water based heating coil	None	Electrical heating coil	Water based heating coil
Ventilation apartments	Only heat recovery	Only heat recovery	-	-
Domestic hot water	DHW tank	Heat booster station (HBS)	DHW tank	DHW tank with electrical heating element

As seen from table 1, the buildings differ in design and installation. The immediate conclusion would be that building 4, due to the age (poor insulation standard) of the building, higher design temperatures of heaters and single-looped radiators, most likely would be the worst performing building. Contrary, building 1, 2, and, 3 are all new, well-insulated buildings equipped with floor heating systems in the apartments and only radiator for the common areas. Therefore, these buildings are likely to be better performing at lower supply temperatures. Due to the DHW circuit design, building 1 and 3 need at least supply temperatures of 60°C to avoid legionella. Contrary, building 2 has a booster HP installed enabling DH supply at 40°C. All buildings have ventilation systems that can be challenging, especially in building 1 and 3, where the ventilation system is controlled separately. If the

[1] DHW shares vary depending on the type of building and the users within the building. Therefore, DHW shares may vary significantly as evident from these test buildings. The DHW is obtained by measuring energy consumptions on the warmest days, assuming that only DHW consumption appears on these days.
[2] Appears as conventional radiators.

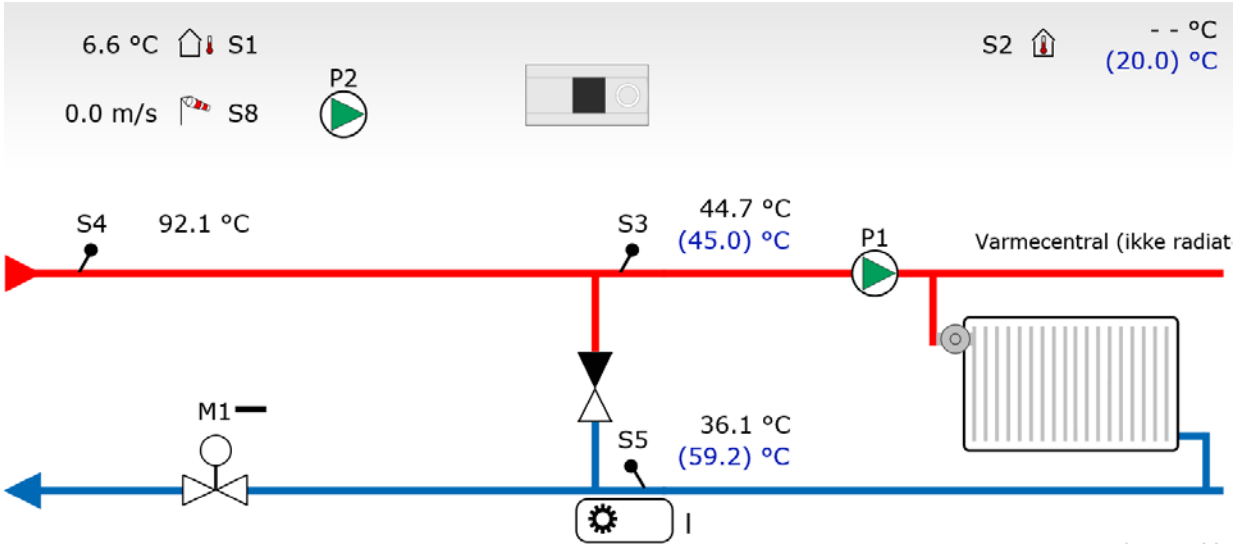
ventilation system is not properly controlled, it take over the primary heating function, which causes an excessive energy consumption as the system is not designed for this purpose.
The pictures and screen dumps below show examples on which add-ons that has been installed in the four test buildings to enable LTDH supply tests. It includes the physical installation of new mixing loops in each of the substations. It also counts the set-up of the online portal of the control system; ECL310, from where temperatures into the substation and each of the heating circuits are controlled.



Building 1: Screen dump of the secondary side in the online ECL portal

Building 3: Mixing loop

Building 4: Mixing loop



Building 2: Screen dump of mixing loop in the online ECL portal

Energy consumption of test buildings

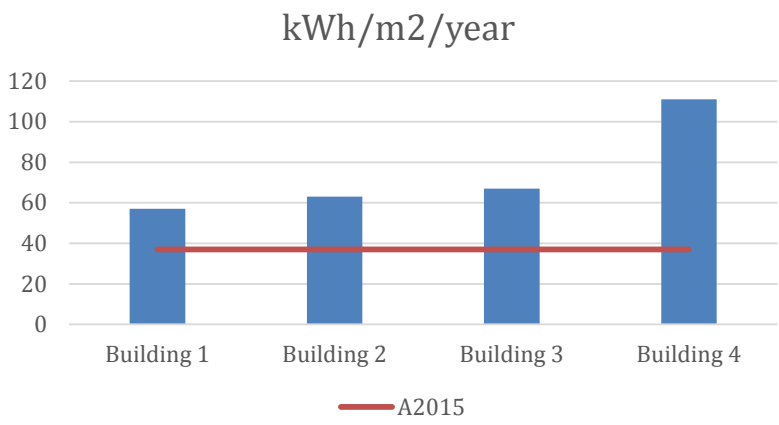


Figure 3: Energy consumption of test buildings in 2017 (HOFOR 2018)[3]

As evident from Figure 3, the three multifamily houses (1,2, and 3) have a rather low energy consumption, compared to building 4. However, according to energy class A2015 requirements (indicated by the straight orange line), the three first buildings should have a maximum consumption of 37 kWh/m²/year assuming an average apartment size at 140 m². The 2017 consumption of the buildings was significantly larger. It indicates that the building heating system do not work as intended. Reasons as to why might be the occupants behavior, errors in the design or/and the operating of the heating system.

Average return temperatures

Table 2: Average monthly return temperatures of test buildings before test start

	Building 1	Building 2	Building 3	Building 4
Marts 2018	42.6°C	41.5°C	42.0°C	58.3°C
July 2018	49.3°C	42.2°C	48.3°C	56.4°C

As evident from Table 2, the building heating system of all demonstration buildings do indeed not work as intended. According to building design criteria, return temperatures should not be above 40°C, see table 1. Still all buildings have return temperatures above during both summer and winter months. However, building 4 performs significantly worse than the three others. Thus, reinforcing the immediate conclusion that this building will have difficulties at lower supply temperatures. Specific to building 2, the DHW is produced by the HBS, which has proven average return temperatures at 30°C, why it is known beforehand that this building's problem is associated with the heating circuit (Thorsen 2018).

Capacity variation of heat demand

The heat demand consist of DHW and space heating. Whereas space heating demand is rather stable, the DHW consumption pattern is shaped according to the rate that people shower, wash hands or do

[3] In this figure, the primary energy factor for DH at 0.85 has not been integrated.

the dishes. The DHW pattern therefore also reflects the type of building as e.g. showers are not typical for commercial buildings.

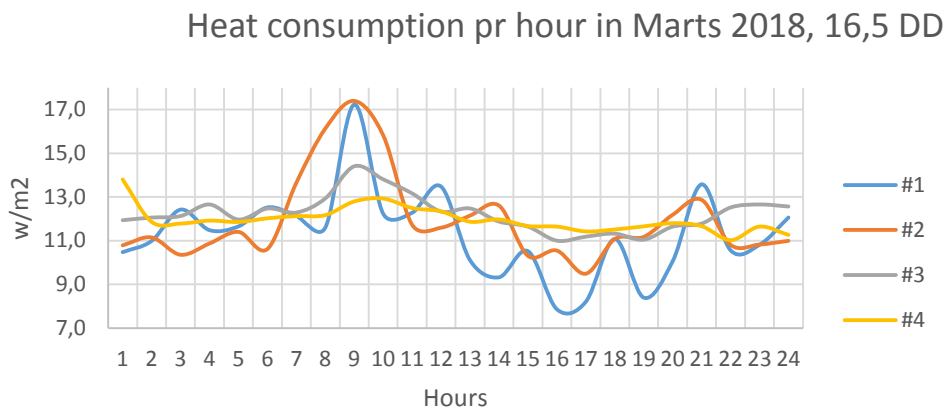


Figure 4: Capacity variation of the four test buildings

All buildings very much correlates with the expected consumption pattern. Hence, the three multifamily houses all have a morning peak (6-10 AM) caused by hot shower, which lead to increased DHW consumption. Contrary, no one showers in the commercial building, and only 4 % of the heat demand is related to DHW consumption. Consequently, this building has a rather flat profile. The morning peak consumption is significantly larger in building 1 and 2 than of building 3, which are similar in size, and construction type. It indicates that there might be a potential for improving the control, or design of the DHW regulation as charging of the DHW tank can be shifted from consumption. Improvements have afterwards been implemented in building 2, where the DHW tank is charged according to hours of low electricity prices. Thus, the consumption pattern of the building looks differently by now (Thorsen 2018).

Short summary of the building presentation

The building have given an understanding of the building design, and the current state of the DH substation in each of the four demonstration buildings.

Building 1, 2 and 3 are all low energy consuming houses that is believed, even on very cold winter days, to handle low supply temperatures. There is however room for optimizing the control of the DH substations in order to improve their performance as reflected by high return temperatures and high heat consumption rates. Building 4 is expected to be challenged when supplied with lower temperatures as the building design and control and/or design of the technical installations is less suited for these kind of operating temperatures, which is confirmed by the in general higher return temperatures and energy consumption than the other test buildings.

3.1 Method

With an offset in the status of the buildings' heating system , as presented above, a test program with reduced supply temperatures has been designed to each individual building. The buildings were all equipped with Danfoss ECL310 climate controllers and mixing loop, enabling control of supply temperatures into each substation. The tests were carried out in intervals of 1 week in which the buildings had a constant supply temperature. After each week, a new supply temperature was tested according to the test program below. The test period was October-December 2018.

Building #1	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
22-10-2018	65	65	65	65	65		
29-10-2018							
05-11-2018							
12-11-2018							
19-11-2018					60	60	60
26-11-2018	60	60	60	60	60	60	60
03-12-2018	60	60	60	60	60	60	60
10-12-2018	70	70	70	70	70	70	70
17-12-2018	70	70	70	70	70	70	70

Building #3	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
22-10-2018	65	65	65	65	65	65	65
29-10-2018	60	60	60	60	60	60	60
05-11-2018	60	60	60	55	55	55	55
12-11-2018	60	60	60	60	60	60	60
19-11-2018	55	55	55	55	55	55	55
26-11-2018	55	60	60	60	60	60	60
03-12-2018	70	70	70	70	70	70	70
10-12-2018	70	70	70	70	70	70	70
17-12-2018	70	70	70	70	70	70	70

Building #2	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
22-10-2018	40	40	40	40	40	40	40
29-10-2018	40	40	45	45	45	45	45
05-11-2018	45	45	45	45	45	45	45
12-11-2018	45	45	45	45	45	45	45
19-11-2018	45	45	45	45	45	45	45
26-11-2018	45	45	45	45	45	45	45
03-12-2018	45	45	45	45	45	45	45
10-12-2018	45	45	45	45	45	45	45
17-12-2018	45	45	45	45	45	45	45

Building #4	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
22-10-2018	70	70	70	70	70	70	70
29-10-2018	65	65	65	65	65	65	65
05-11-2018	60	60	60	60	60	60	60
12-11-2018	60	60	60	60	60	60	60
19-11-2018	65	65	65	65	65	65	65
26-11-2018	70	70	70	70	70	70	70
03-12-2018	70	70	70	70	70	70	70
10-12-2018	70	70	70	70	70	70	70
17-12-2018	70	70	70	70	70	70	70

Figure 5: Supply temperature test program of the 4 demonstration buildings. Red cells indicate that the building has not been tested, while the different shades of blue indicates the supply temperature, which is also written with a number.

Sensors installed on the heating and DHW circuits enabled data extraction. Thereby, a detailed observation and analysis of the operation of the substation was possible. However, cooling on the primary side of the heat exchanger into each substation constitute the main evaluation criterion on the performance of the buildings.

This evaluation criterion is selected because it determines the hydronic capacity in the distribution grid of Nordhavn. The more each building cools the DH water the less water need to be transported. Thereby, the DH company will save electricity consumption of pumps or alternatively reduce supply temperatures and realize lower heat losses. A high cooling also indicates that return temperatures are low which brings a high efficiency of production plants. Therefore, cooling is an important parameter to evaluate, when implementing lower DH operating temperatures.

To evaluate the cooling performance of buildings' at the different supply temperatures, an expected cooling has been set up for each supply temperature. The expected cooling of each level of supply temperature is visualized in the table 3. The expected cooling is an assumption based on building installations in Nordhavn being design for 60/40°C. It is assumed that buildings supplied with 40-45°C have a Heat Booster Substation installed, utilizing the DH water as heat source.

For simplicity, a linear relationship between supply and return temperature is assumed as seen in Table 3. The expected cooling is establish to enable comparison across the buildings, regardless of each buildings heating installation design.

Table 3: Expected cooling depending on supply temperature

Supply temperatures	Expected average cooling
70°C	30°C
65°C	27.5°C
60°C	25°C
55°C	22.5°C
45°C	17.5°C

40°C	15°C

3.2 Results

The cooling results from the test program are visualized on figure 6 and 7. Due to the condition of the building heating system, not all buildings were tested at the same supply temperatures.
Regarding to LTDH tests (55-70°C supply), results showed that independent of building type, the tendency was a reduced cooling the more the supply temperature was reduced. Moreover, whenever outdoor-temperatures dropped below 10°C, there was a tendency towards poorer cooling performance. It is problematic as a high cooling is more important at lower outdoor temperatures where hydronic loads are larger and capacity problems might occur.
The results indicates the need for better operation of the building heating system.
A contradicting tendency was evident in the ULTDH test of building 2 where cooling was rather stable independent of outdoor temperatures. The variating cooling results may be caused by variating tests of the operation of the HBS, which has been carried out concurrent with the test of ULTDH. Moreover, a bypass installed in the DHW circuit which bypasses more water at higher outdoor temperatures causing a contradicting pattern as of the LTDH test buildings.

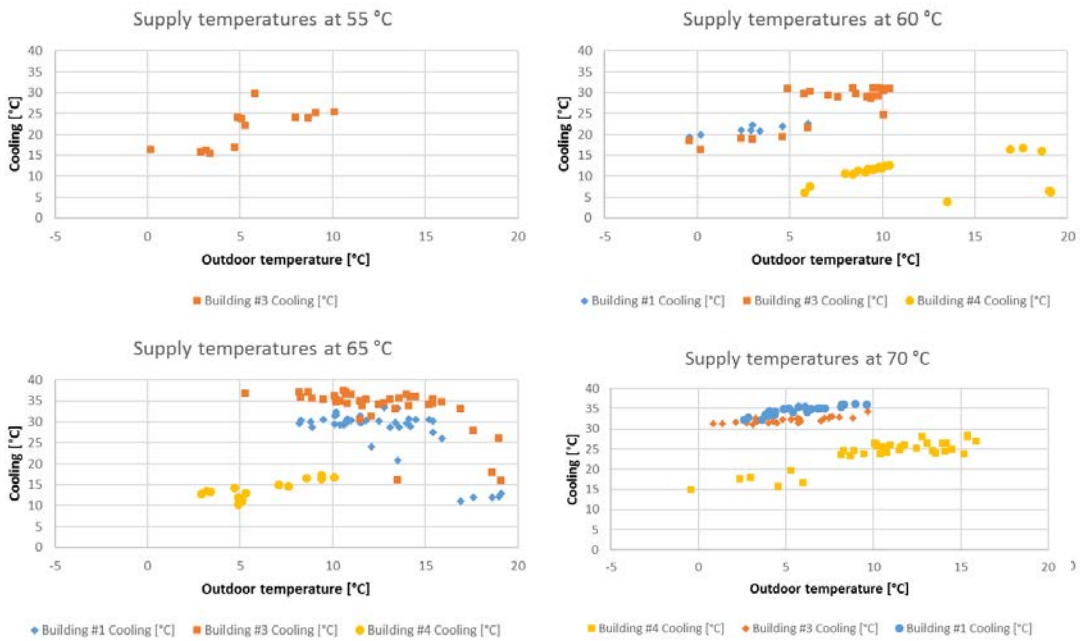


Figure 6: LTDH tests: daily cooling result combined with the outdoor temperature of each test buildings

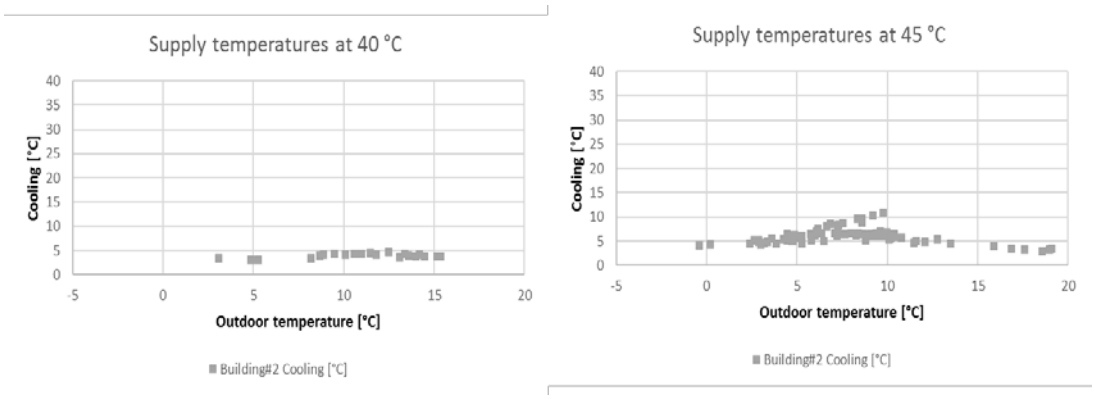


Figure 7: ULTDH test: daily cooling result combined with the outdoor temperature of each test buildings

The LTDH tests revealed a huge difference between the performance of the individual buildings. The best performing buildings were building 1 and 3, which provided cooling above expected cooling on most days. Contrary, building 4's cooling performance was consistently below the expected, see table 3.

The ULTDH test revealed a remarkably bad cooling at 5-10°C, well below the expected 15-17.5°C, which was mostly caused by poor performance of the space heating circuits, as the DHW circuit cooled in between 10-15°C. Had the circulation HP's capacity been increased in the HBS, the cooling from the DHW circuit would potentially reach 20°C (Thorsen 2018)

Faults in the substations

This section documents some of the faults that lead to a poor cooling.

Poor cooling originated from wide range of faults, being poorly corrected heating curves, malfunctioning sensors, dislocated heaters, poorly designed DHW circuits, temperature requirements for DHW and lastly under-dimensioned heaters and over-dimensioned heating components.

<u>Example 1 – poorly corrected heating curve</u>

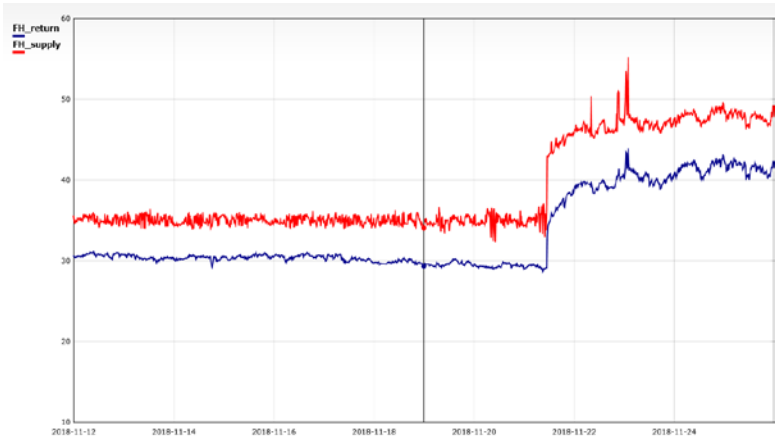


Figure 8: Graph of supply and return temperature of the combined floor and radiator circuit of building #3 during a two week period.

This graph reveal how a costumer complaint caused the heating manager to adjust the heating curve by increasing supply temperatures with 10°C into the heating circuits. The adjustment significantly

decreased the performance of the substation. Whereas costumer complaints are not desired, better efforts should be given in identifying a more optimal supply temperature set-point.

Example 2: Supply temperature vs set-point temperature

When set-point temperatures comes too close to supply temperatures, the valve opens completely trying to reach the set-point temperature, which increased hydronic loads. Such errors may in traditional systems most frequently be seen in radiator circuits with high temperature requirements, causing set-point temperatures too close to the DH supply temperature. In LTDH areas these problems may also be witnessed in the DHW circuit. Figure 9 visualizes such a case where DH supply temperatures are reduced from 60°C to 55°C. The red curve show the measured temperature in the DHW tank while the blue curve shows the return temperature from the DHW tank.

It reveals that when DH supply temperatures are reduced to 55°C, it will unavoidably cause poor cooling. Additional, set-point temperatures at 55°C cannot be sustained, and therefore legionella prevention cannot be guaranteed as recommended by the Danish Standard (DS439 / 2009). While some research suggest that DH supply temperatures should be lowered to 55°C (Lund et al 2017), it is clear that either lower DHW set-point temperatures should be accepted or a different DHW design that boosts the DHW temperature to 55°C is needed to go beyond 60°C supply and towards a 55°C supply. Generally, it should be avoided to have set-point temperatures too close to the DH supply temperature in any circuit.

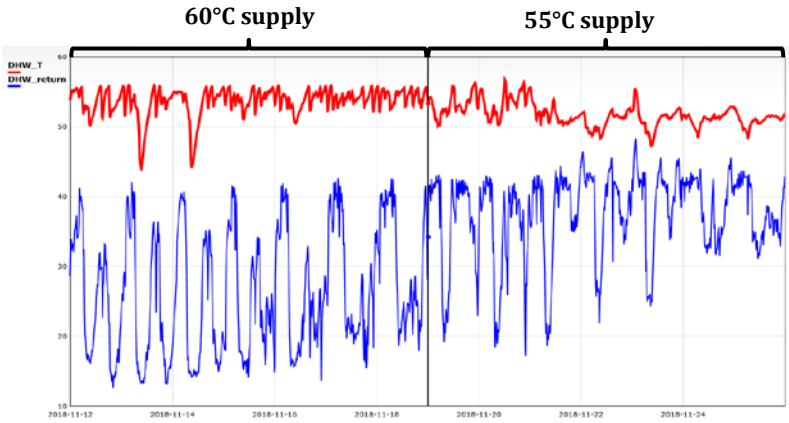


Figure 9: Graph of supply and return temperature of the DHW of building #3

Example 3: Malfunctioning sensors

Figure 10 reveal an issue of a malfunctioning sensor. Despite, no lack of heat in the apartments of building 2 (no customer complaints in the heating season), the measurements tell us that no heat has been delivered through the floor heating circuit. Hence, both return and supply temperatures equal approximately 33°C. It indicates that probably sensors are malfunctioning. Malfunctioning sensors prevents an optimal operation of the heating circuit, because set-point temperatures cannot be accurately tuned.

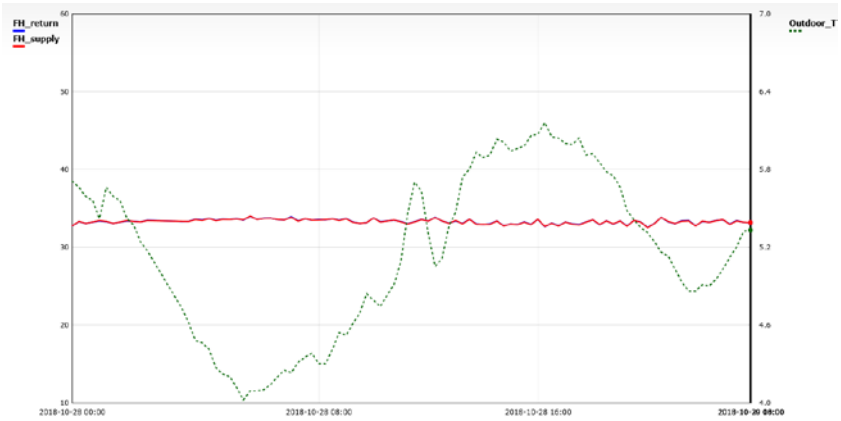


Figure 10: Measurements of building 2's floor heating circuits the 28th of October

Example 4: Radiators in common areas:

Floor heating is the recommended heating installation for low temperature supply, but in some areas floor heating is considered infeasible as it can be difficult to install, e.g. in common areas such as stairways and basements. Therefore, radiators are preferred to common areas in the buildings in Nordhavn. These heaters can be problematic to lower supply temperatures, if they are under-dimensioned for the desired comfort temperatures. Figure 11 shows the case of the radiator circuit in building 2, where DH supply temperature were at 40°C[4]. The circuit delivers a return temperature at approximately 37°C, thus severely hampering the cooling of the building.

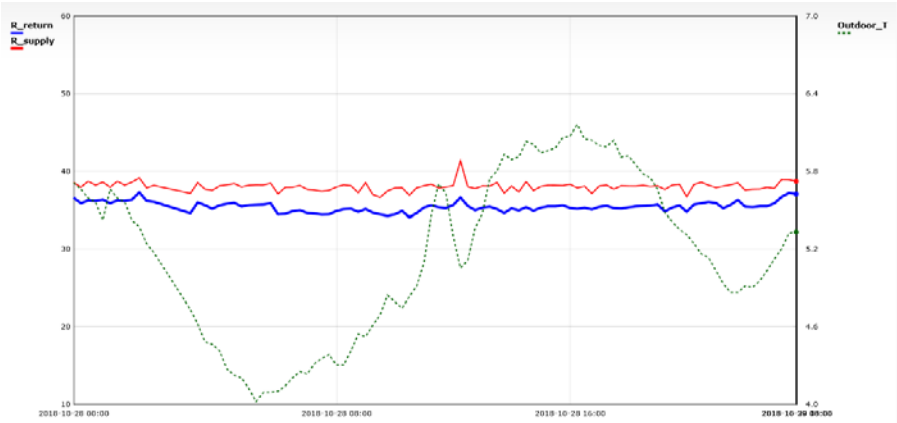


Figure 11: Measurements of building 2's radiator circuits the 28th of October

Summary of building performance and faults

Table 4 visualizes the evaluation of the buildings' cooling performance at a given supply temperature. Each building has been marked with a green circle, if the building performs well. A yellow circle when small measures are needed to achieve the desired cooling. Red, if a more comprehensive change is needed.

[4] It should be noted that the supply temperatures into the radiator circuit does not change with the pattern of the outdoor temperature, because the circuit is already supplied with the highest achievable supply temperature at 40°C DH supply conditions.

Table 4: Summary of faults occurring in the buildings at different supply temperature

Faults of the substation	Expected average cooling	Building 1	Building 2	Building 3	Building 4
70°C supply	30°C	🟢		🟢	🟡
65°C supply	27.5°C	🟢		🟢	🔴
60°C supply	25°C	🟡		🟢	🔴
55°C supply	22.5°C			🟡	
45°C supply	17.5°C		🟡		
40°C supply	15°C		🔴		

Data extractions, combined with on-site visits of the substations have been used to identify what caused a poor performance of the building. The reasons as to why the buildings cannot maintain a sufficient cooling, are described below.

Building 1 – new multifamily house	**Building 2 – new multifamily house (ULTDH)**
This building failed to deliver sufficient cooling at supply temperatures at 60°C. Hence, cooling at 60°C supply ranged from 20-23°C. Insufficient cooling was caused by too high return temperatures from the DHW circuit, which struggled to elevate temperature to 55°C. Too high supply & return temperatures (50/40°C) from of the radiator circuit also contributed. The operation of the floor heating circuit could not be evaluated, due to potential sensor failures. Moreover, the lack of a differential pressure regulator, caused cyclic control.	This building delivered insufficient cooling at supply temperatures of 40°C and 45°C. Hence, cooling ranged from 5-10°C. Influencing factors were an under-dimensioned heat exchanger and high return temperatures from the radiator circuit returning 35-37°C. Sensors into the floor heating circuit are likely to be malfunctioning, therefore the circuit could not be evaluated. The DHW circuit proves to be the best functioning part of the substation in this building delivering acceptable cooling which was caused by the HBS.
Building 3 – new multifamily house	**Building 4 – old commercial building**
This building failed to deliver sufficient cooling at supply temperatures of 55°C. Cooling ranged from 15-30°C. It was caused by too high supply temperatures into the heating circuit. Moreover the DHW circuit failed to deliver reference tank temperature of 55°C.	This building could not be supplied with temperatures below 70°C. Lower supply temperatures involves a comprehensive renovation and relocation of radiators. Moreover, the DHW tank should be larger.

As ventilation systems data was not obtained in any of the buildings, their contribution to poor cooling is unknown.

4 Heating supply options of Nordhavn

In this chapter, the focus is moved from the buildings to the potential heating supply options of Nordhavn. In the chapter different supply scenarios are analyzed to find the best business-economic scenario.

The heating supply scenarios of Nordhavn are analyzed with 2035 as reference year. Details of this is shown in Table 5. Generally, the scenarios differ in technologies, DH operating temperatures and in presence/absence of collective grid connection.

Table 5: Supply scenarios of Nordhavn

Supply scenarios	#1 Collective DH	#2 Collective LTDH	#3 Island ULTDH (Heat Booster Substations)	#4 Island ULTDH (electric boilers)
Temperature levels [°C]	70/40	60/35	40/25	40/25
Grid loss	7%	6%	4%	4%
Net heat demand of Nordhavn [MWh] (67% space heating/33% DHW)	119,798	119,798	119,798	119,798

The selection of the main heat production technologies and temperatures levels in the scenarios reflects the aim of implementing more HP's as stated in the heat plan of Greater Copenhagen (CTR, VEKS and HOFOR 2014), as well as the availability of sea water as the only larger heat source in the district.

In all scenarios, temperature elevation of DHW is the chosen legionella disinfection method, because it constitutes the only economically attractive solution. Other solutions includes mechanical and sterilization techniques, but these have not yet been commercialized (Karlsson and Ottoson 2018) (Sernhed 2018).

The local DHW production units as of scenario 3 and 4 (HBS and electric boilers) are selected as the each have very distinct qualities. The HBS allows for a high efficiency of the heating system, while the electric boilers have low investments costs which may make it more cost-efficient.

Temperature levels are designed to match:

1. A supply temperature of what HOFOR originally intended to deliver to Nordhavn; 70°C
2. A LTDH supply at 60°C which requires no extra local temperature boost of the DHW
3. A ULTDH supply at 40°C, which is boosted locally to 60°C, accounting temperatures losses of up to 5°C.

Scenario #1 and #2 are moreover characterized with the presence of a connection to the collective DH grid through a mixing loop. Scenario #3 and #4 have no connection to the main collective grid of HOFOR. Since the collective grid is not present to act as both back up unit and storage, these scenarios are also equipped with back up units and storage. An electric boiler and an steel storage tank are considered the most cost efficient technologies for the purpose. All scenarios except scenario 1 have been designed with a seawater HP for baseload production. Seawater as a heat source is chosen due to

Nordhavns location at the seaside, the large heat capacity of the heat source and the relatively small temperature variation in the heat source. As such, the scenarios can be visualized as in figure 12.

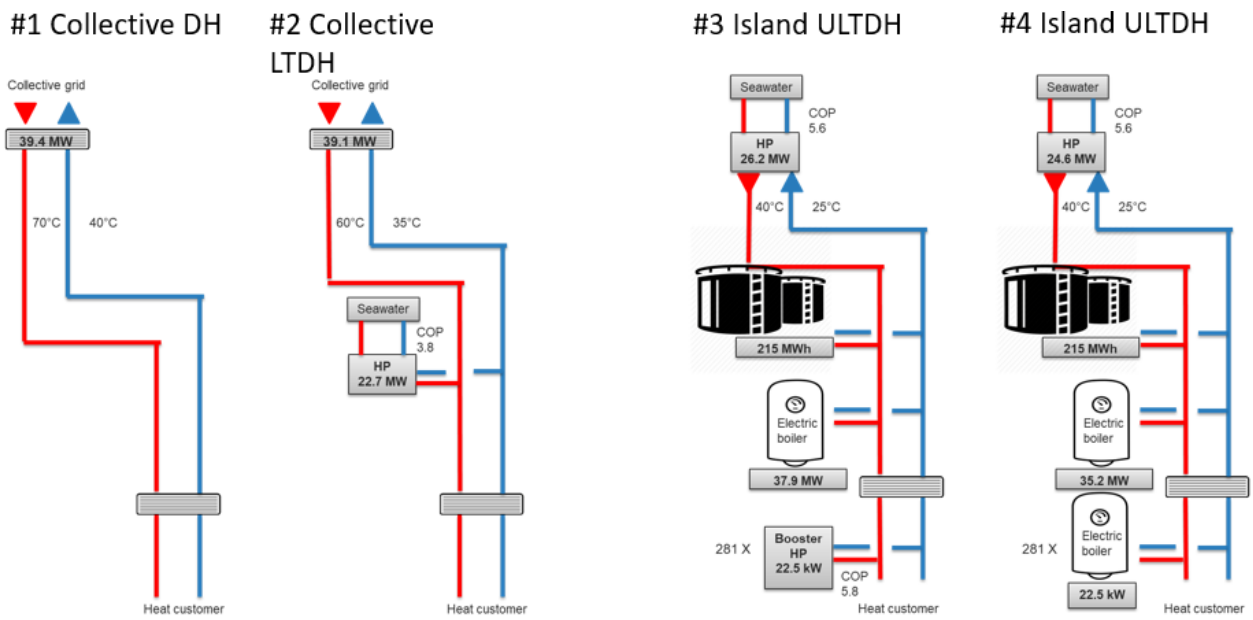


Figure 12: Diagram of heating supply scenarios of Nordhavn

4.1 Method

In this section, the heating supply system method used to evaluate the scenarios are presented. Likewise, assumptions, which are fed into the energy system model (EnergyPRO), are presented. The steps of the heating supply system analysis are as follows:

1. <u>Sizing technologies</u>
   The first step is to identify the optimal size of technologies in each scenario. Optimal size is determined by step-wise increasing sizes of each technologies until there is no positive effect on the net present value. The net present value calculation includes costs of producing heat every hour in a year, and yearly cost of investing in more capacity.
2. <u>Yearly operational costs:</u>
   The production in each scenario is optimized in steps of 1 hours, to ensure lowest heat production costs, while fulfilling the predicted heat demand of Nordhavn by 2035. Determination of lowest hourly heat production costs include electricity taxes, tariffs and HOFOR's electricity price projection of 2035. Variable operational costs of each production unit in the scenario is included. The costs of buying heat from the collective grid is included, reflecting the projection of HOFORs energy system model (Balmorel) by 2035.
3. <u>Annuities</u>
   Investment cost of each scenario is considered by calculating the yearly costs of the investments by means of the formula below

$$P_{pc} = \mathrm{P_{tc}} * \frac{r}{1-(1+r)^{-n}} \qquad [1]$$

$P_c = Yearly\ investment\ costs$ [€]
$\mathrm{P_{tc}}$ = Total investment cost [€]
$r = Discount\ rate$ [%]

$n = Lifespan\ of\ technology\ [Years]$

For this purpose, a discount rate at 3.5% and the lifespan of each individual technology is applied. These are found in table 6. Investments costs are not only considered for production and storage units, but also electricity grid reinforcement and heat DH grid expansion in the future area of Levantkaj.

4. Heat price
   A yearly heat price is calculated of each scenario by adding the operational costs and annuities of each scenario and divide it with the total heat demand in the year of 2035.

$$H_c = \frac{O_c + P_c}{h_d} \qquad [2]$$

$h_d = Heat\ demand\ \ of\ Nordhavn\ [MWh]$
$O_c =$ Operational costs [€]
$H_c = Heat\ price\ [€/MWh]$

5. Sensitivities
   Each scenario is changed in two different ways to investigate how different conditions influence the scenarios. In the first sensitivity, electricity prices are increased by 20%. In the second sensitivity, scenario 3 and 4 become grid connected like scenario 1 and 2. Thereby, storage and back-up units of scenario 3 and 4 are replaced by the collective grid connection. Heat prices of both sensitivities are calculated.

Assumptions

Investment costs assumptions are visualized in table 6. Investment costs of the HBS should be treated with caution. Hence, it is based on projection on the economies of scale achieved by investing in a HBS at 22,5 kW, yet the largest HBS on the market is currently 14 kW (Meesenburg 2018). As the reference year is 2035, it is considered a realistic that a 22,5 kW will exist on the market by then.

Table 6: Investment cost and lifespan of technologies applied in the supply scenarios

Investment cost and lifespan	**Estimated costs**	[years]	Source
Seawater HP	740,000 [€/MW]	25	(DEA 2016; HOFOR 2018)
Electric boiler, peak load	60,000[€/MW]	20	(DEA 2016)
Heat Booster Substation, DHW[5]	432,000[€/MW]	20	(Meesenburg 2018)
Electric boiler, DHW[6]	199,000[€/MW]	25	(Meesenburg 2018)
Grid connection, mixing loop	13,423[€/MW]	40	HOFOR
Thermal storage	165-190 [€/m3]	40	(Rambøll 2016)

[5] Add on costs to a normal substation
[6] Add on costs to a normal substation

The technology specification are visualized in table 7. It should be noted that due to differences in DH operating temperatures, the seawater HP has a higher COP in scenario #3 and #4 compared to scenario #2. It should also be noted that the booster HP of scenario #3 utilize the return pipes as heat source. It brings a high COP, but also a larger production from the seawater HP than of scenario #4. The average COP of the booster HP is 5.77, under the assumption that a Lorenz efficiency at 40% can be achieved. Scenario #4 purely uses electricity to boost the DHW. It brings a higher electricity consumption than of the other scenarios.

Table 7: Technology specification and sizes

	#1 Collective DH	#2 Collective LTDH	#3 Island ULTDH (Heat Booster Substations)	#4 Island ULTDH (electric boilers)
Maximum thermal effect	39.4	39.1	37.9	35.2
Mixing loop [MW]	39.4	39.1	-	-
Sea water heat pump [MW]		22.7	26.2	24.6
Sea water heat pump COP, 50% Lorentz efficiency		3.79	5.58	5.58
DHW total size/unit size [kW]			4,700/22.5	4,700/22.5
Electric boilers [MW]			37.9	35.2
Storage in Nordhavn [MWh]			215	198
Electricity grid, reinforcement [MW]		6.9	37.9	35.2

The sizing of DHW units in the ULTDH follows a different method. Hence, the sizing is not considered as an optimization problem. Rather it has been assumed that the average substation in Nordhavn supplies 60 apartments and a heated area of 8400 m2. Moreover, it assumed that such substation would have a peak demand of 126 kW (EH&P, 2008). The peak heat demand is mostly covered by the storage tank in the substation. The storage can presumably be charged by a Heat Booster Substation or electrical boiler at 22.5 kW. (Thorsen, 2018) A total of 211 average sized substation has been estimated for the entire DH project area in Nordhavn.

4.2 Results

This section introduces the results of the heating supply scenarios and sensitivities of each scenario. It is concluded which scenario is the most preferable from a business economic perspective.

The yearly heat price of each scenario can be seen in figure 13. The lowest heat price is achieved in the LTDH scenario (#2) being 40 €/MWh with a margin of 5 €/MWh to scenario 3 which has a heat price at 45€/MWh.

The results from the two sensitivities make it evident that increased electricity prices has the most negative impact on scenario #4. Both scenario #2 and #3 is moderately impacted. It underpins that a system operated with heat pumps is more resilient towards increased electricity prices than when electric boilers are used for DHW production. As the entire heat supply system of Greater Copenhagen

has not been modelled, the influence of electricity price could not be investigated on scenario #1. However, as the heat supply system has various types of heat producing technologies a larger degree of resilience towards changes in electricity prices are expected.

In the second sensitivity, where all scenarios were connected to the collective grid, scenario #3 and #4 performed significantly better. Suddenly, the difference in heat price between scenario 3 and 2 is insignificant. This is caused mainly by two reasons. First, with no need for electric boilers as back-up unit, large savings in electricity grid reinforcement are achieved. Moreover, the collective grid serves as a cheaper peak load unit, than the electric boilers. It is a combination of investment and operational savings, that bring scenario 3 and 4 closer to scenario 2 in terms of cost-efficiency.

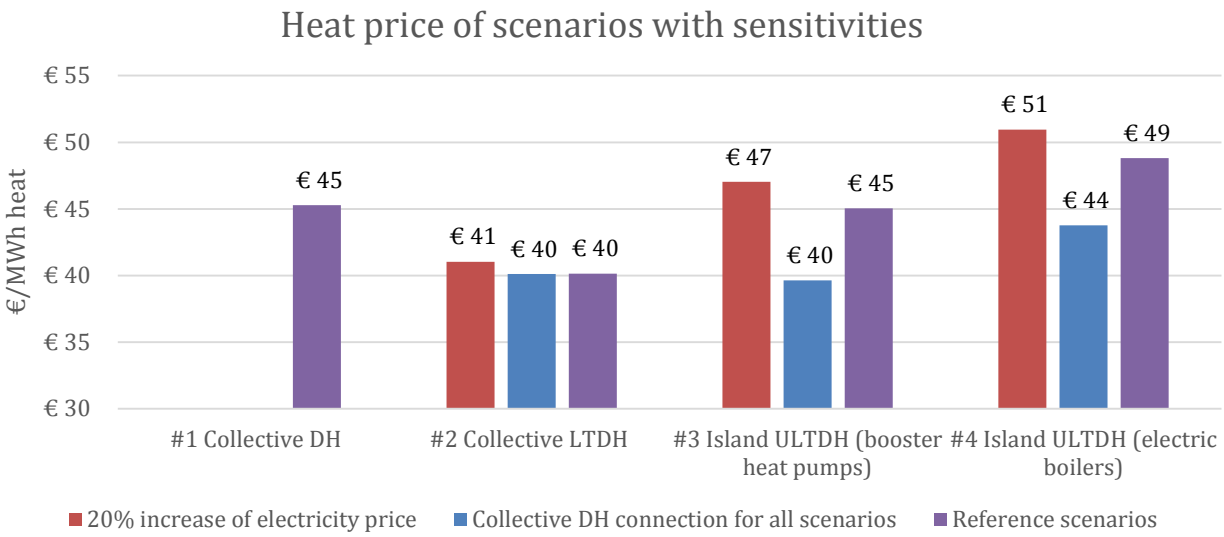


Figure 13: Heat price of baseline scenario and sensitivities of each heating supply scenario

Short summary

It can be concluded that from a business economic perspective that investing in a local seawater HP is economically more attractive than just connecting Nordhavn to the collective grid in scenario #1. Moreover reducing operating temperatures from the reference of 70°C down at LTDH seems beneficial. If going for an ULTDH supply, DHW should not be produced by electric boilers, but by booster HPs, because operational savings achieved by booster HPs more than counterbalance the higher investments costs.
In all scenarios, operational costs constitute the largest share of the yearly costs compared to yearly annuities. Investment costs are highest of the ULTDH scenarios, because larger seawater HPs are needed and electricity back-up units entail large electricity grid reinforcements.

Different financial conditions and scenario set-up might change the conclusion. Changes in electricity prices and in access to the collective DH grid has been investigated. It was clear that scenarios based purely on electricity producing units are more sensitive than scenarios with access to various production sources. The impact is the more the greater, when electricity-consuming units have a low efficiency. A collective DH grid connection seems as a better solution than operating a DH grid in Nordhavn as an island.

5 Grid expansion options of Levantkaj Nordhavn

Most DH companies seek to optimize operating temperatures in the grid. In practice in means that supply temperatures are reduced, when outdoor temperatures are high, and the other way around when outdoor temperatures are low. In HOFOR's distribution grid, it results in DH operating temperatures ranging from 65-95°C. However, when expanding DH grids, the dimensioning criteria does not take into account how preliminary increased supply temperatures can increase the capacity in the grid. Rather pipe dimensions are determined from an average expected cooling and the maximum expected hydraulic load. Therefore, the grid might end up being over-dimensioned. Over-dimensioned grids might hamper approval of grid expansion projects for LTDH areas, because grid costs become overly expensive.
This section investigates the business-economic consequences of design criteria that better reflects the reality of how DH cooperates their grids. This is relevant to Nordhavn, as the subarea of Levantkaj need a completely new distribution grid to enable DH supply.

5.1 Method

The traditional grid design method, applies a design temperature of -12°C. The temperature refers to the heat load that is expected at outdoor temperatures of -12°C. As seen on Figure 8, temperatures never drops below -12°C in a normal year, therefore there will never be the need of increased supply temperatures to increase grid capacity.

This analysis considers dimensioning standards that captures temporary increased supply temperatures. For the purpose, an excel model has been developed that compares design temperatures of -12°C, -3.5°C and 5.5°C.
-12°C is selected because this is the DH Company's applied design temperature. -3.5°C is chosen because, as seen from Figure 14, only very few hours occur with temperatures below -3.5°C and consequently very few hours would need increased supply temperature compensation, while the dimensioning heat load would be considerably smaller. The selection of 5.5°C as design criterion, requires approximately 3000 hours of increased supply temperatures to generate more grid capacity, according to figure 14. This criteria is selected because from such design criteria, the dimensioning heat load will be very small, while also still being able to supply the high temperatures on the coldest days in a year, with HPs, which according to Chapter 3 is the preferred heat production method in Nordhavn.

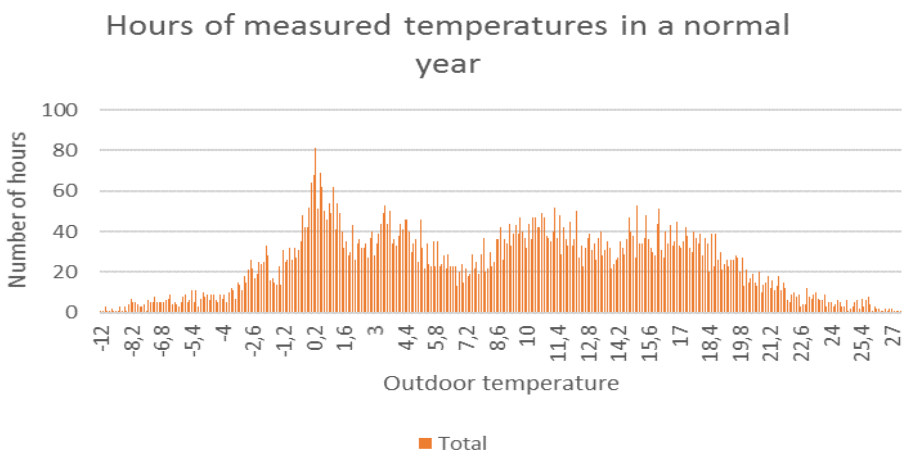


Figure 14: Hours of temperatures occurred in a normal year (EMD 2010)

Model description
In the excel model, supply temperatures are calculated for those hours where outdoor temperatures are below the design criteria. To identify the influence on the heat production costs, the analysis build upon the different heating supply options, see Chapter 3.
The pipe layout in the model of Levantkaj is simple, being 4,800m distribution pipes, divided into 100m sections. The heat demand is assumed to be linearly decreasing. The grid fulfill velocity-threshold of maximum 3.5 m/s and total pressure losses below 9.5 bar.

The stepwise built up of the model are as follows:

1. Identify maximum hydraulic load of each design criteria
2. Identify pipe size of each design criteria
3. Identify supply temperatures in hours with outdoor temperatures below design criteria
4. Identify heat losses, pump expenses, grid investment cost and influence on heat production costs

Each step is described in more details below.

Step 1 – determining hydraulic load
The hydraulic load is identified by calculating the hourly heat demand and determining the water flow rates.
The heat demand of Levantkaj is assumed to be approximately 45,000 MWh, but to identify the heat demand during each hourly outdoor temperature, the heat load of each hour is calculated from formula 3. The formula assumes that the heat demand is disproportionate with the outdoor temperature.

$$Thermal\ effect\ [MW] = 0.41\ MW * (17°C - x°C) + b \qquad [3]$$

The constant: b, distinguishes the heating supply scenarios, see Chapter 3, from one another and ranges from 0.8-1.8 MW, depending on heat losses and local DHW production.

The water flow rates at each 100m has been determined from formula 4. Depending on planned DH operating temperatures. Cooling varies from 15-30°C, see Table 5, Chapter 3. Thus, the heating supply scenarios have different water flow rates.

$$Q = \frac{h}{C * \rho * \Delta T} \qquad [4]$$

$h = Thermal\ effect\ in\ an\ hour\ with\ outdoor\ temperatures\ below\ design\ criteria\ \ [kW]$
$\Delta T = Cooling\ at\ outdoor\ temperatures\ below\ design\ criteria\ [C°]$
$C = heat\ capacity\ of\ water\ [4{,}18\ \ kJ\ /\ kg°C]$
$\rho = Applied\ heat\ density\ of\ water\ [1000\ kg/m^3]$
$Q = water\ flow\ rate\ [m^3/s]$

(Poulsen et al 2015)

Step 2 – Selection of pipe sizes
Pipe sizes in the model of Levantkaj are identified by applying formula 5

$$DN(i) \geq \sqrt{\frac{Q}{v}} \qquad [5]$$

$v = Velocity\ \ [m/s]$
$Q = water\ flow\ rate\ [m^3/s]$

To reflect the reality of a limited number of pipe sizes offered by the pipe supplier, the pipe sizes of table 8 has been used.

Table 8: Pipe sizes, costs and u-values of the pipes considered in the analysis (HOFOR 2018)

DN	D(i)	Estimated pipe costs €	Heat loss coefficient (u-value of the pipe)	
Pipe size	**mm**	**[€]**	**[W/m*C]**	**Type of pipe**
15	13	872	0,124	Twin pipes
20	20	1.026	0,158	
25	25,6	1.026	0,151	
30	32	1.065	0,15	
40	39	1.065	0,171	
50	51	1.091	0,189	
65	66	1.091	0,243	
80	93,9	1.176	0,33	
100	107,1	1.232	0,246	Single pipes
125	132,5	1.360	0,279	
150	160,3	1.448	0,318	
200	210,1	1.641	0,33	
250	263	1.832	0,318	
300	312,7	1.983	0,363	
350	344,4	2.144	0,411	
400	393,8	2.424	0,482	

Step 3 – Calculation of supply temperature time series

To identify how many degrees the supply temperature must be increased, to compensate hydraulic loads higher than the design situation, formula 6 has been applied. It calculates the additional desired cooling in the grid of each hour where the outdoor temperature is colder than what the grid has been designed for.

$$\Delta T = \Delta T_r + \frac{(h - h_1)}{q * C * \rho} \qquad [6]$$

$h = Thermal\ effect\ in\ an\ hour\ with\ outdoor\ temperatures\ below\ design\ criteria\ \ [kW]$
h_1 = Thermal effect design criteria situation [kW]
$\Delta T = Cooling\ at\ outdoor\ temperatures\ below\ design\ criteria\ [C°]$
$\Delta T_r = Cooling\ in\ design\ situation\ [C°]$
$C = heat\ capacity\ of\ water\ [4{,}18\ \ kJ\ /\ kg°C]$
$\rho = Applied\ heat\ density\ of\ water\ [1000\ kg/m^3]$
$q = Water\ flow\ rate\ [m^3/s]$

Step 4 Design criterion's influence on heat price

To evaluate the business economic costs of each pipe layout scenario of Levantkaj, all costs of heat losses, pump expenses and grid costs has been calculated as the costs of one year in operation. Heat losses are calculated using heat loss coefficients as of table 8 and prices as of table 9. Electricity costs of pumps are calculated assuming 80% pump efficiency and an average pressure gradient ranging from 40-80 [Pa/m] in design situation. Grid costs have been annualized by the use of Formula 1.

Table 9: Cost assumptions for heat and electricity (own assumption on costs of 2035 including taxes and tariffs)

Unit	Cost of heat	Cost of electricity
[€/MWh]	50	100

A new supply temperature time series that results step 3 has been used as input in calculating new operational costs as of formula 2. Thereby, a new heat price for each heating supply scenario in Nordhavn has been calculated.

5.2 Results

The results of the analysis is structured into four parts. First, the design criterion's influence on pipes sizes are presented. Secondly, the influence on supply temperature, thirdly the influence on grid costs and lastly the influence on heat price.

Pipe sizes

On figure 15, it is demonstrated how changing the design criteria to either -3.5 or 5.5°C will result in smaller pipes. While the figure only shows results from a distribution grid with DH operating temperatures as of heating supply scenario 2, the same tendency counts other DH operating temperatures.

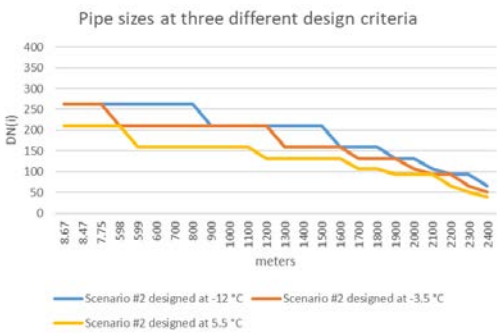


Figure 15: Design criterion's influence on pipe sizes. The example is the supply pipe in the heating supply scenario 2

Supply temperatures

Figure 16 demonstrates the consequences of investing in smaller pipes as supply temperatures increase when outdoor temperatures drops below the design criterion. Thereby, ensuring enough hydraulic capacity in the grid throughout the year.

It is evident that threshold supply temperatures are reached when designing the grid at 5.5°C. Scenario #1 reach supply temperatures up at 100°C. Scenario #2, #3 and #4 reach supply

temperatures at 90°C, 60°C and 60°C, respectively. As seawater HPs only exist in #2, #3 and #4, designing at 5.5°C might be possible in all scenarios. However, supply temperatures are increased above the reference system temperatures in more than 3000 hours, when applying the design criteria of 5.5°C. In contrast, designing grids at -3.5°C, supply temperatures only need to be increased for 250 hours. Maximum supply temperatures are at 80°C of scenario #1, whereas for ULTDH scenario #4, maximum temperatures are at 45°C.
Applying the standard -12°C design criteria, the grid can be operated at constant supply temperatures.

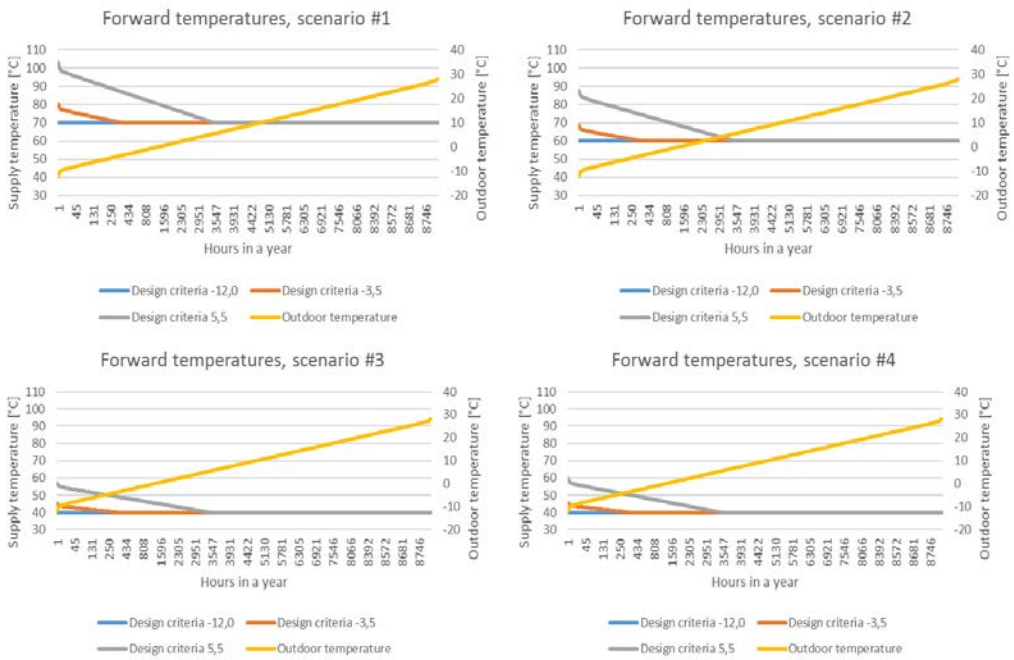


Figure 16: Supply temperatures caused by changing design criterion

Influence on heat price

Figure 17 shows how total cost of the grid decrease as design temperature increase. The total cost of grid includes the annuity of grid investments, heat losses, and pump expenses.
The grid costs constitute the largest share of the total costs, heat costs follow as the second most contributing cost factor, whereas the pump expenses neglectable. However, increasing design temperature entail opposing tendencies among the cost components. Hence, pump expenses increase, while grid costs decrease, and the heat loss costs are almost unchanged.
The reason to increased pump expenses, is due to the fact that smaller pipes, as seen in figure 15, entail a larger pressure loss (see table 8), and therefore more pumping power.
Decreasing costs of pipes are obviously also due to the smaller pipes that cost less, see table 8.
Costs of heat losses involve counterbalancing effects. On the one hand, increasing design temperature, lead to increased supply temperatures that lead to increased heat losses and also costs. On the other hand, heat losses are reduced because higher design temperature entail smaller pipe dimensions and therefore a smaller surface area for heat losses.

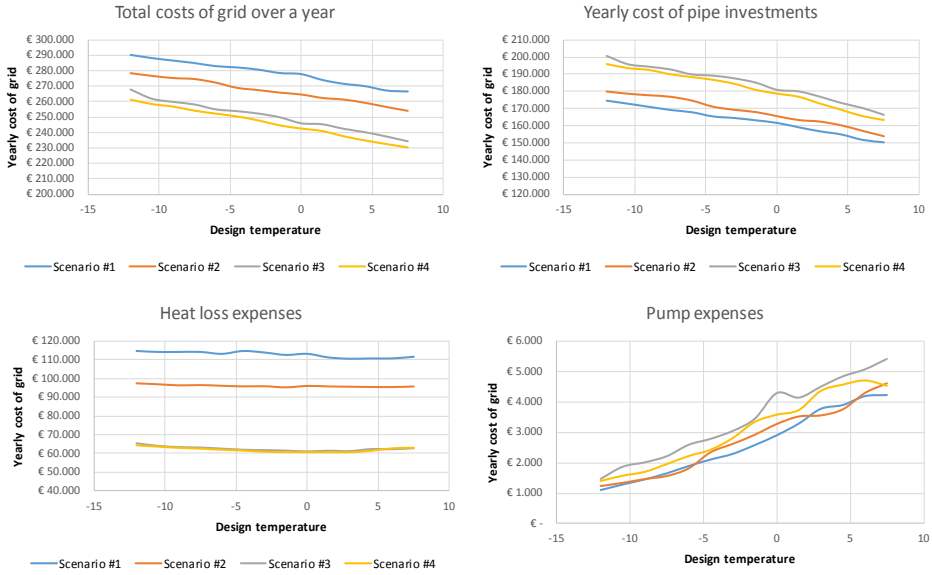


Figure 17: Different design criteria and the associated costs of pipes, heat losses, pumps' electricity consumption and the combined cost over a year. Assuming a discount rate of 3.5% and 40 years lifespan

However, the most relevant cost factor would be the final heat price. The influence of changing design temperature on the overall heating price is visualized in Figure 18. It is evident that yearly business economic savings are achieved in all scenarios, when applying the design criterion of -3.5°C, instead of -12°C. However, a design criterion of 5.5°C results in increased costs in all scenarios except the reference scenario, because the HP's suffer from more than 3000 hours of increased supply temperatures. The results also indicates that design criterion in general would benefit from being adjusted to the prevailing production units in the grid expansion area. In this specific case of Levantkaj with the seawater HP as the prevailing production unit, the design criterion of -3.5°C is preferred from a business economic perspective.

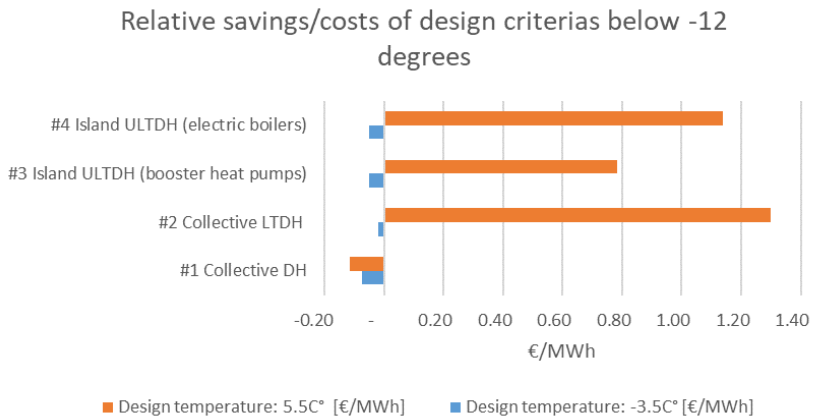


Figure 18: Yearly savings from changing grid design criterion

Short summary

Instead of sizing pipes for a heat demand rarely occurring (-12°C design), supply temperatures can be increased. Increasing supply temperatures on days colder than the design temperature, allows for smaller pipes and cost savings.

Comparison of pipe sizes in Levantkaj, Nordhavn, designed for a heat demand occurring on a day of -12°C, -3.5°C and 5.5°C, revealed -3.5°C to be the most cost efficient design criterion.

6 Recommendation

In this section, recommendations for lowering DH operating temperatures are given. The recommendations are specific to Nordhavn, but might be applied in other DH grids with a similar setting.
Generally, the analyses came to conflicting recommendations. Hence, the building heating system analysis found that the desired cooling of the four substations could not be achieved for supply temperatures below 70°C. The cooling problem only grew, the more supply temperatures were lowered, which lead to less efficient heat production units and potentially grid capacity problems. Contrary, the heating supply analysis found that a LTDH supply at 60/35°C is preferable, when a seawater HP is installed and the grid of Nordhavn is attached through a mixing loop to the collective grid. From the grid expansion analysis, it was found that overall savings could be achieved in the grid design phase, when supply temperatures are increased as outdoor temperatures drops below -3.5°C, which follows from choosing the more cost-efficient -3.5°C as grid design criterion. Moreover, grid costs would be further reduced, the better cooling that is expected in the design phase.

To bridge the findings of the three analyses, it is recommended that efforts are focused on improvements on the building heating systems of Nordhavn as it currently prevent business economic savings from being harvested at production and grid level.

It is recommended that improvements focus on:

- The old and worst performing buildings
- Introducing more intelligent control systems
- Decrease sensor faults
- Heating circuits for common areas
- Timed temperature elevation for DHW production

The old and worst performing buildings

Costs of improving building heating systems in Nordhavn could easily counter-balance the cost reducing DH operating temperatures at 60/35°C. Therefore, efforts should be focused on the worst performing buildings. In chapter 2 the old commercial building performed significantly worse from a cooling perspective than the new multifamily houses. Additionally, the building had the highest energy consumption. Consequently, the building puts a larger hydraulic load to the grid and influence the efficiency of heat production more negatively than other buildings. Starting improvements with an offset in the worst performing buildings would results in immediate benefits.

Implement intelligent control system

It is proposed that that more intelligent control of the heating system is implemented. Such intelligence should come with heating load forecasts, automatic adjustment of heating curves, and integration of ventilation systems in the DH system. Benefits of better return temperatures and lower energy consumption are promised (Vogler-Finck 2018).

The promises of the intelligent control system do indeed match the problems encountered in the demonstration buildings. As concluded in Chapter 2, manual and human interaction in the substation did cause too high supply temperatures into the heating circuits, which result in worse cooling and more heat losses.

Decrease sensor faults

Sensors in the substation enable fault detection of the different circuits and enable a smart operation of the substation as described above. A prerequisite for these benefits to be harvested is well functioning sensors. Unfortunately, this was not always the case of the four demonstration buildings in this report. These buildings had sensors of outdoor, return, supply, and DHW tank temperatures installed, some of them were found to be either dislocated, inaccurate and without signal, which resulted in an inefficient substation operation. Some of these problems originate from certified plumbers or installation contractors that are inexperienced with the set-up. The amount of errors and mistakes were surprising to HOFOR considering that 3 out of 4 buildings were newly built buildings.

Install return temperature limiter

The common areas (stairways and cellars) in the test buildings, all demonstrated the poorest performance of all heating circuits as both supply and return temperatures from these circuits were too high for LTDH supply. The problem arise most likely from either under-dimensioned radiators, under-dimensioned transport pipes, or thermostatic radiator valves turned up to max. While upgrading to larger dimensions would solve the problem, it would be expensive and cannot be offered by a DH company. If the problem is in the control of the radiator, it could easily be solved by adjusting turning the valve to a new set-point. However, it may be turned to max again by an unknowing occupant and therefore it would not be a permanent solution. Meanwhile these areas are merely passage areas and therefore thermal comfort is not as important as within the apartments. Consequently, reducing the target temperatures in common areas would be an easy an effective way of achieving lower operating temperatures in the radiator circuits. Occupant behavior and preferences might oppose this solution.
Occupant behavior can on the other hand be mitigated by introducing return temperature limiters on the heating circuits. Such installation consists of a valve that regulates according to the measured return temperature. When the return temperature is too high, the valve closes and limits the flow. Some DH companies already apply it, and it ensures low return temperatures. This method risk reducing the occupants' thermal comfort, but ensures great cooling.

Timed temperature elevation for DHW production

As evident from Chapter 2, the DHW production had problems reaching set-point temperatures at 55°C. Regulation requires that temperatures can be raised for legionella disinfection at 60°C (DS469-2013 and DS439). If a 55°C supply cannot enable 55°C in the DHW tank, 60°C supply would neither enable 60°C in the DHW tank. Consequently, the introduction of LTDH supply at 60/35°C should come with timed supply temperature elevation one or two times a week in only a few hours. Legionella bacterias are eliminated within 10-25 min at supply of 60°C (Karlsson and Ottosson 2018) (Yang, Li and Svendsen 2016) (WHO 2007) and therefore timed temperature elevation are considered enough to avoid legionella disinfection.

7 Conclusion

Nordhavn is a new district of Copenhagen located by the sea. Some parts of Nordhavn has been built and consists of mostly new buildings and a few older buildings. By 2035 Levantkaj will be added to the district. The new buildings of Nordhavn makes lower DH operating temperatures possible, and therefore, the district is intended for supply temperatures of maximum 70°C.

However, the performance of the buildings in Nordhavn at lower supply temperatures are to this point yet unknown. Furthermore, the heat supply in the remaining parts of Nordhavn is still to be decided. Three analyses were carried out investigating technical and business economic aspects of LTDH/ULTDH supply temperatures.

The first analysis was a technical analysis of four buildings' performance at reduced supply temperatures. The buildings were located in Nordhavn and reflected the types of buildings that can be found in Nordhavn. Three buildings were new multifamily houses, whereas one was an old commercial building. All buildings were equipped with similar control system, and the new buildings had floor heating installations and radiators in common areas, whereas the old building had only radiators installed. All buildings had a storage tank for DHW. Moreover, one of the multifamily houses had a booster HP installed enabling a ULTDH test. The booster HP cooled the DH supply and produced DHW at 55°C.

The buildings has been tested in a two month period from late October to late December in 2018 at supply temperatures ranging from 40-70°C. Measurements of cooling on the DH side of the customer installation, and measurements of each of the circuits were carried out on each building, except one without measurements on the circuits.

The test results revealed that great cooling was measured at supply temperatures at 70°C. Acceptable cooling can be achieved down at supply temperatures of 60°C for buildings equipped with floor heating, whereas the old buildings heating system nearly collapsed, cooling only 5-15°C. Supply temperatures at 40-45°C was tested in one building with a poor cooling outcome, ranging from 5-10°C. A malfunctioning heating circuit caused it.

The second analysis investigated business economic outcomes of four different supply scenarios of Nordhavn by 2035. These were:

1. A collective DH grid scenario (70-40°C), in which Nordhavn is separated and supplied through a mixing loop into the collective DH grid.
2. A LTDH scenario (60-35°C), in which Nordhavn has its own seawater HP combined with a collective DH grid connection
3. An island-ULTDH scenario (40-25°C), including a seawater HP, thermal storage, electric boilers for back-up, and <u>booster HPs</u> for DHW production at 55°C.
4. An island-ULTDH scenario (40-25°C), including a seawater HP, thermal storage, electric boilers for back-up, and <u>electric boilers</u> for DHW production at 55°C.

The results of the business economic analysis revealed that scenario 2 and 3 had the lowest yearly cost, considering operational cost as well as investment costs of production units, electricity reinforcement and DH grid. Costs of 3 were lower than of 4, because the booster HP resulted in less electricity consumption than producing DHW with an electric boiler. It more than counterbalanced the higher investment costs.

Moreover, sensitivities revealed that high electricity prices caused significantly higher costs to

(ULTDH)-island scenarios, because they did not access alternative heat production unit. Having all scenarios connected to the grid, the ULTDH scenario 3 were again competitive with the LTDH scenario The third analysis, aimed at identifying design criteria that could drive grid investment savings. The analysis demonstrated that changing design criterion from -12°C to -3.5°C on the grid expansion in Levantkaj, could drive yearly savings in all heating supply scenarios, in despite of periodically higher supply temperatures and an associated poorer seawater HP performance.

From the analyses it was concluded that a LTDH supply is the most feasible, but efforts should be put in the building heating system to push for an improved cooling. Measures should be focused on the worst performing buildings and includes

- Introducing more intelligent control systems
- Decrease sensor faults
- Heating circuits for common areas
- Timed temperature elevation for DHW production

Prospective work

Future works on the implementation of lower DH operating temperature should focus on at least three aspects. These are

- Generalizability of LTDH case studies
- Regulatory framework
- Motivation for change

Other new urban areas exists that are comparable with the building stock of Nordhavn. Can results from Nordhavn be generalized to other new urban areas? And under which conditions? Despite urban areas being built within the same period of time, there might still be important differences, such as the design of the heating system and installations, the production units in the DH network and the availability of heat sources. These differences could essentially change the recommended DH operating temperature. An investigation that identifies the boundaries of how results can be generalized would be of great interest.

The regulatory framework, understood as mostly taxes and tariffs, should be investigated to identify if these are actually pushing the best development of DH operating temperatures for society. As evident from Chapter 3, electricity prices hugely affect the business economic viability of the different scenarios. Generally, as reducing DH operating temperature are associated with an increased electrification of the heating sector, the more important it becomes to identify adequate electricity cost level, which ensures investments and viability of the right technologies and operating DH temperature levels. An analysis of heating supply scenarios that disregards current regulatory framework, but considers investment costs, operation costs and heat production efficiency would enable suggestions on how policies should be designed to foster the right development of DH operating temperatures to the society's best.

Motivation for change is much needed when it comes to the building heating system, because the cooling performance is worse than expected i.e. return temparatures are higher than expected. Heat costumers are owners of the building heating system and are responsible for the operation of it, but are currently not handling it well enough. Investigation of what motivates the heat customer is

needed, so DH companies can implement the right policies to motivate them. The investigation might focus upon already existing policies and their ability to drive change. Some example on different policies are cooling tariffs, return temperature tariffs, list of poor performing costumer, performance labels and service subscription.
Moreover, new ULTDH scenario set-ups could be investigated. Would it e.g. be viable to supply new urban areas like Nordhavn with the DH return pipe of neighbouring areas? Such set-ups will have an even more positive influence on the return temperatures and thereby the efficiency of the production plants. The investigation should be accompanied with an investigation on the potential of developing different heating tariffs, where costs depend on which DH temperature level the heat customer consumes.

No matter what, the work toward supplying green, safe and affordable district heating continues…..

8 References

Construction support, H., 2018. *District heating temperature requirements,* Copenhagen: Internal minute.

Copenhagen Municipality 2009. *Copenhagen Climate Plan – the short version.* August 2009. Online: https://www.energycommunity.org/documents/copenhagen.pdf

Copenhagen Municipality 2015. *Sundmolen I Nordhavn.* Lokalplan nr 524. Approved 3. July 2015. Online: https://kajplads2150.dk/assets/documents/global/Lokalplan-524-Sundmolen.pdf

CTR VEKS and HOFOR, 2014. *Varmeplan Hovedstaden 3 - Omstilling til bæredygtig fjernvarme,* Copenhagen: DH utilities of Greater Copenhagen

DEA, August 2016. *Electricity and District heating generation,* Copenhagen: Danish Energy Agency

DS, D. S., 2009. *Code of practice for domestic water supply installations*, Charlottenlund: Dansk Standard

DTCHA 2018*. Tidligere Bygningsreglementer*. Copenhagen: Danish Transport, Construction and Housing Authority. Online: https://historisk.bygningsreglementet.dk/tidligerebygreg/0/40 Lund,

EH&P, 2008. *Guidelines for district heating substations,* s.l.: Euroheat & Power.

EMD International, 2010. *Danish Reference Year 2010,* Region of Zealand: EMD - International.

HOFOR, 2018. *Energykey - heat consumption measurements,* Copenhagen

Honeré, K 2018.. *Information on building mass in Nordhavn.* 2018.

Karlsson, L. & Ottoson, K., 2018. *Overcoming issues with Legionella in DHW LTDH systems,* Lund: Lunds University

LUND, H. et al., 2018. The status of 4th generation district heating: Research and results. *Energy*, 1 December, pp. 147-159.

Meesenburg, W., 2018. *Prices on individual booster units based on inputs from Danfoss and Metrotherm.*

Månsson, S., 2018. Faults in DH substations. Aalborg, 4GDH Conference

Rambøll 2016. Varmelager Teknologikatalog. February, Report.

Sernhed, K., 2018. *Solutions and regulations to with legionella problems in district heating systems.* Aalborg: 4GDH Conference.

Thorsen, J. E., 2018. *Phone meeting about the heat booster station.* Danfoss.

Poulsen et al., 2015. *Varme Ståbi.* Teknisk forlag, 7. udgave, 2015. Isbn13: 9788757128543

Vogler-Finck, P. J., 2018. *Reducing supply temperatures in existing buildings with an innovative advanced heating curve control technology.* Aalborg: 4GDH

WHO, 2007. *Legionella and the prevention of legionellosis.* ISBN 92 4 156297 8 red. Printed in India: World Health Organization.

Yang, X., Li, H. & Svendsen, S., 2016. Alternative solutions for inhibiting Legionella in domestic hot water systems based on low-temperature district heating. *Building services engineering - research and technology*, pp. 468-478.