Heat Booster Substation for Domestic Hot water and Circulation Booster for Domestic Hot Water Circulation

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1: Heat Booster Substation for Domestic Hot Water and
2: Circulation Booster for Domestic Hot Water

Danfoss/DTU
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Kevin Smith/Eduard Melo Oliver
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Confidential deliverable ☐

Preface

EnergyLab Nordhavn – New Urban Energy Infrastructures is a lighthouse 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 further can contribute in solving the major climate challenges the world is facing.

Budget: The project has a total budget of DKK 143 m (€ 19 m), of this DKK 84 m (€ 11 m) are funded in two rounds by the Danish Energy Technology Development and Demonstration Programme (EUDP).

Forord

EnergyLab Nordhavn er et fyrtårns 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.

Disclaimer

Not relevant for this deliverable.

Project Information

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Executive Summary

This report includes two new developed, installed and tested concepts as part of the Energylab Nordhavn project[1]:

1: A **Heat Booster Substation** (HBS) in Aarhusgade 140 - Havnehuset, a multifamily building with 22 individual flats, was installed in February 2018. The HBS is a district heating (DH) substation operating at an ultra-low temperature DH (ULTDH) supply temperature of 35-45°C. The concept includes a main electric heat pump, boosting the DH supply temperature to a level where domestic hot water (DHW) can be produced by means of an instantaneous heat exchanger. The HBS concept takes energy from the ULTDH supply and by the heat pump a part of the flow is cooled down by the evaporator and returned to the ULTDH return, and with this energy the other part of the flow is boosted by the condenser and led to the DH storage tank. Besides this, the HBS maintains the DHW circulation temperature by means of a small heat pump. No external heat source is needed as both heat pumps move the energy originating from the ULTDH supply. The DH storage tank is accumulating the energy, and this storage tank makes it possible to shift the charging time of the tank, independent on the DHW tapping occurrence. Hereby the service of load shift flexibility is provided in relation to electricity and DH. The heating service of the building is supplied with ULTDH as well but is not a part of this WP. The ULTDH is realised by a mixing-loop on building level.

Based on the experience made (12 months so far), it can be concluded that the HBS unit is successfully installed, tested and operating. The DHW is produced at 55°C, DHW circulation is raised continuously from 50-55°C, with a DH supply temperature of 45°C and a DH return temperature of typically 30°C. The share of electric energy consumption for DHW and DHW circulation service is 14%, at the average produced DHW volume of 1.700 liters pr. day. Whereas the DH share is the remaining 86%. Due to the variation of DHW draw off pr. day over the year, the electric share varies e.g. from 12%, at a produced DHW volume of 2.500 liters pr. day, to 17% at a produced DHW volume of 1.000 liters pr. day. Note that electric share is based on DHW as well as DHW circulation production.

The daily average DHW load shift potential is 75 kWh/day for the 22-flat building, hereof electricity accounts for 7 kWh/day and thus DH accounts for the remaining 67 kWh/day. On a yearly basis it's at least on the same level as the load shift potential for the heating system of the building. Regarding capacity flexibility, this is 3 kW electric and 30 kW DH realized for e.g. a period of 1 hr. and 10 min. before the morning DHW peak and before the evening DHW peak in average over the year.

Regarding fuel shift flexibility, which is obtained by varying the evaporation temperature of the main heat pump, tested in the range corresponding to a DH return temperature from 20°C to 30°C, this result in 2 kWh pr. day, thus the electric consumption can vary from 6 to 8 kWh for an average day, with the corresponding DH variation from 66 to 68 kWh/day. The Fuel shift flexibility is regarded as minor.

A prognosis and economic based scheduling of the HBS charging is implemented, optimizing for lowest energy costs, latest possible charging among the lowest cost periods and observing the constrains of min. and max. charging level of the tank. By charging the tank as late as possible the heat loss from the tank is reduced due to a lower surface temperature.

A number of feasibility studies has been made for the HBS concept compared to the LTDH concept with different energy sources, showing under the current tariffs system the concept is very limited economically feasible, say only feasible under special system conditions. For a new urban development area, like Nordhavns Levantkaj, the HBS concept could become relevant. This type of area could be designed for ULTDH, where the DH energy input should be

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[1] www.energylabnordhavn.dk

the DH return water from the existing DH system. This temperature is typically in the range 35-45°C, and thus relevant for the HBS concept. Still adjustments to the current energy price structures will be needed to make the concept feasible. Also, where the source of energy for DH is at low temperature level, e.g. solar thermal, geothermal, industry surplus and data centres, the concept of HBS in combination with underfloor heating is relevant to consider. Further, the value of the load shift potential, temperature dependent DH energy prices both flow and return and the electric energy prices will determine if the HBS concept is feasible in each individual case.

2: A **Circulation Booster** (CB) is installed in Strandboulevarden 3, a multifamily building with 15spacious apartments. The aim was to secure a low DH return temperature from the DHW system, where especially the DHW circulation caused a high DH return temperature, due to the relative high heat loss of the DHW circulation system. The CB is boosting (heating) the DHW circulation water from 50°C to 55°C in two steps, by means of a direct heat exchange and a heat pump booster, using DH at normal temperatures (70 – 100°C) as the energy source. The DH return temperature is reduced from a level of approx. 45°C to approx. 20°C for the DHW service (DHW preparation and DHW circulation).

Based on the experience made (6 months so far), it can be concluded that the CB is successfully installed, tested and operating. The DHW circulation is boosted continuously from 50-55°C, with a DH supply temperature in the range from 70-100°C. The share of electric energy consumption for the CB concept is 17% at a representative DH flow temperature of 80°C. The representative DH return temperature from the CB is 23°C (not including the DHW storage tank DH return). Within the range of DH flow temperatures 70 – 100°C, the electric share is in the range 20- 15% of the energy needed to boost the DHW circulation. The remaining energy source is DH, with a share of 80 – 85%.

Load shift is not possible for this concept, since the CB is running continuously, and energy storage devices are not obvious for this concept.

Fuel shift is possible, to a minor degree, realized by influencing the condenser outlet temperature, and thus influencing the balance of heat from the condenser and the direct heat exchange. No tests are so far made in this regard.

A number of economic scenarios have been made, focussing on different bonus structures related to reduced DH return temperature and electric energy costs. The current tariff structure does not give a feasible economic case for the CB concept. But considering a more progressive bonus scheme for providing a low DH return temperature, the market potential could be interesting in the segment of existing buildings and partly also new buildings with DHW circulation systems. This is also supported by having the simple retrofit demands in mind and driven by the argument that a low DH return temperature is the precondition for a low DH flow temperature, which is one of the characteristics of the 4th generation DH concept.

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2.0	2019-05-17	Torben Ommen/Wiebke Meesenburg	Added text and Review
2.0	2019.05-22	Kevin Smith/Eduard Melo Oliver	Added text and Review
3.0	2019-05-30	Jan Eric Thorsen	Verified and updated document for Review
4.0	2019-06-12	Per Nørgaard	Review
5.0	2019-07-01	WPL Group	WPL approval

Quality Assurance

Author	Reviewer	Approver
Jan Eric Thorsen et. al.	Per Nørgaard	Jan Eric Thorsen

Status of deliverable		
Action	**By**	**Date**
Sent for review	[Jan Eric Thorsen et. al]	**2019-05-30**
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Verified	[Jan Eric Thorsen, Danfoss]	**2019-06-13**
Approved	WPL group	**2019-07-01**

1. Heat Booster Substation for Domestic Hot Water

1.1 Introduction

As part of the Energylab Nordhavn project, Danfoss has installed a heat booster substation (HBS) in a multifamily building named Havnehuset, located at Aarhusgade 140. The HBS concept takes energy from the ULTDH supply and by a heat pump, a part of the flow is cooled down by the evaporator and returned to the ULTDH net, and with this energy the other part of the flow is boosted by the condenser and accumulated in the storage tank at a temperature suitable to produce DHW. The substation is operating with ultra-low temperature district heating (ULTDH) at supply temperatures of 35-45°C. It comprises a heat pump to enable the preparation of domestic hot water (DHW) at temperatures above the ULTDH supply temperature and a storage tank. Reducing the district heating (DH) temperature level is highly relevant going towards the 4th generation of DH, where lower temperatures are a key enabler for utilising a higher share of available low-grade heat sources[2]. Further, the concept of load shift is an important part of the 4th generation DH. Some of the benefits by reducing the DH supply temperature is reduced heat losses in DH network, it’s easier to integrate available surplus heat at low temperature level such as geothermal heat, solar heat, industrial surplus heat, supermarket excess heat, etc. ULTDH HBS may be an important enabler for integrating higher shares of renewables and waste heat in the DH network. Further it increases the efficiency of central plants, e.g. heat pumps. The HBS secures a low DH return temperature from the DHW part of the service and it opens the opportunity to connect a building area to the existing DH return line without increasing hydraulic capacity in existing network. Further, the HBS introduces load shift flexibility, by offering the opportunity to schedule the operation of the heat pump according to electricity and heat price signals or such that electrical and heat demand peaks are avoided. To a limited degree also fuel shift flexibility (shifting between DH and electricity as energy supply) can be provided.

1.2 The field site building – HBS in Havnehuset

The HBS installed in the central technique room in Havnehuset is supplying DHW and DHW circulation to 22 flats by 8 risers.10 flats are in a 5-storey setup, and 12 flats are in a 3-storey setup. The HBS was installed February 2018.

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[2] Lund. H, et al., 4th Generation District Heating (4GDH), Energy (2014)

Figure 1: Havnehuset, located at Aarhusgade 140.

The HBS consists of four parts, the prefabricated substation or HBS module (including valves, meters, sensors, controllers, pipes, heat exchanger for DHW and electrical cabinet), a prefabricated large heat pump booster (main) for the DH tank charging, a prefabricated small heat pump for boosting the DHW circulation temperature and two DH storage tanks of each 750 liters volume.

Figure 2: Heat Booster Substation installed and operating in Havnehuset.

The four modules can be seen in Figure 2, where the two heat pumps are in the lower right part of the photo.

For the purpose of the experimental evaluation, the HBS system is installed as an add-on to the existing DHW system, which can be re-engaged and hereby function as a back-up system. The existing heating system is operating in the traditional way but at ULTDH temperatures. In Figure 3 it is shown how the HBS is integrated into the existing heating and DHW installation.

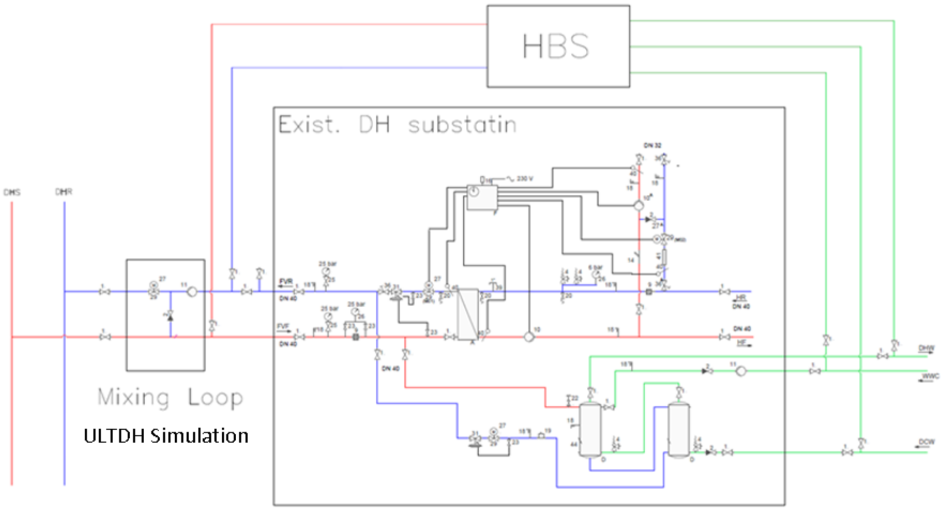

Figure 3: Heat Booster Substation integration in existing system.

A mixing loop is installed to simulate ULTDH temperatures by mixing the DH supply at typically 70 – 100 °C with water from the DH return line. The mixing loop is established as a part of WP5 of the EnergyLab Nordhavn project.

1.3 HBS layout

With the supply temperatures of DH below the needed temperature for producing DHW at 55°C by a direct heat exchange process, the temperature must be raised or boosted. For this purpose, an electric driven heat pump was applied. In the developed HBS concept, this temperature boost was obtained by use of a heat pump at the primary side, which utilized the DH supply as the heat source and the heat sink. In cases where the DH network is used as the heat source, it is important that a significant share of the heat input to the DH system originates from natural or renewable resources, such as renewable energy, solar thermal units, or waste heat, such as flue gas condensation, for the ULTDH system to exceed the performance of systems with low temperature DH[3&4]. The conceptual layout of the system was chosen from a range of designs, to obtain the best thermodynamic performance of the HBS, and with it the highest coefficient of performance of the heat pump, for any DH supply between 35°C and 47°C[5].

Due to capacity costs and the start-up dynamics of a heat pump, a tank for heat accumulation was introduced. The tank also enables load shifting in relation to electricity as well as DH consumption. Due to legionella risks, it was decided to

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[3] Ommen T, Markussen WB, Elmegaard B. Heat pumps in combined heat and power systems. Energy 2014;76:989–1000. doi:10.1016/j.energy.2014.09.016.

[4] Elmegaard B, Ommen TS, Markussen M, Iversen J. Integration of space heating and hot water supply in low temperature district heating. Energy Build 2015. doi:10.1016/j.enbuild.2015.09.003.

[5] Ommen T, Elmegaard B. Exergetic evaluation of heat pump booster configurations in a low temperature district heating network. Proc Ecos 2012 - 25th Int Conf Effic Cost, Optim Simul Environ Impact Energy Syst 2012:1–14.

place the tank on the primary side and use an instantaneous heat exchanger for heating the DHW when tapped. The HBS was designed and sized for operation in a multifamily building like Havnehuset.

The developed HBS is shown in Figure 4. The tank volume is divided into two, due to accessibility of the technical room of Havnehuset. The two heat pump boosters are separated as well, due to both accessibility and flexibility.

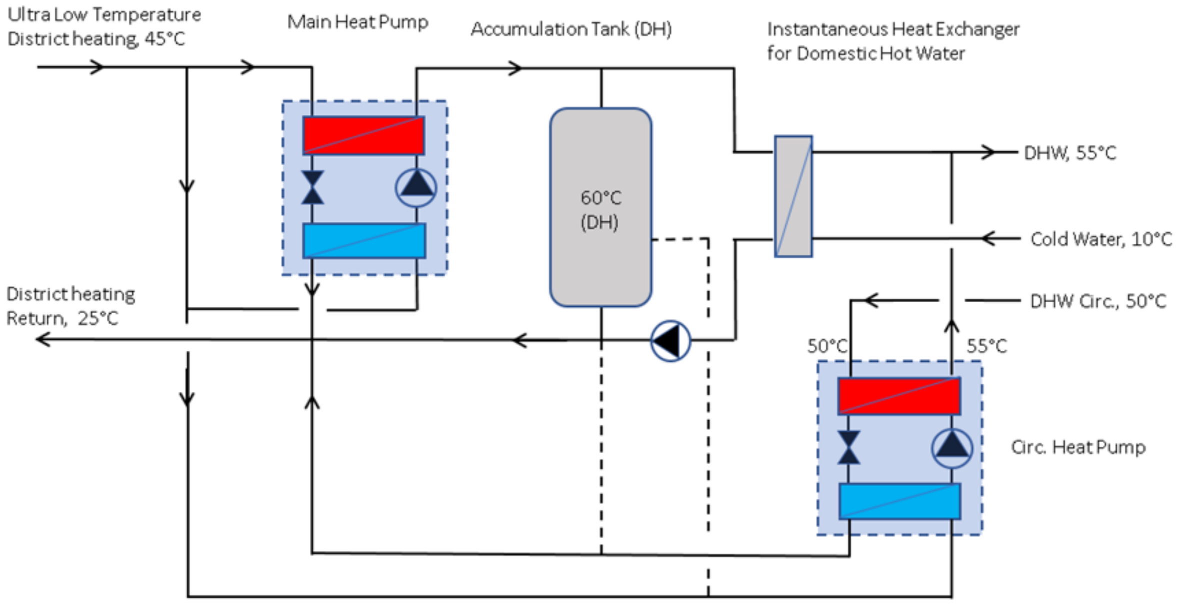

Figure 4: Basic scheme of HBS as installed in Havnehuset

Only the main components are shown in Figure 4. E.g. control valves, pumps, flow meters, temperatures, energy meters etc. are not shown. The Danfoss ECL310 is controlling the HBS and is also used as the getaway for data logging and transfer for analysing and optimization of the HBS operation.

1.4 Operational principles for HBS

The principle is that the DH supply flow is split into two. The first part is led trough the condenser of the main heat pump, where it is heated or boosted to 60°C-65°C and afterwards let into the DH accumulation tank (charging). The second part is led trough the evaporator, providing the source energy for the heat pump and is cooled down to 20-30°C, typically 25°C.

With a significant part of the DHW heat demand used for DHW recirculation, i.e. maintaining a high comfort level and securing short waiting times for hot water, it is likely that the DHW circulation may impact the DH accumulation tank by loss of the thermal stratification and quick discharge. To prevent this, a separate heat pump was applied with the primary purpose to maintain the DHW circulation temperature. The principle of the circulation heat pump is the same as the main heat pump, but where the energy source is either the ULTDH supply, or, in case the temperatures are suitable, lukewarm water from the bottom of the accumulation tank. The building space heating circuit was operated in parallel to the DHW system and is not a part of the HBS concept, and thus not described further.

1.5 Basic operation of the HBS

Field data was logged continuously, and examples are presented below in plots with the time on the x-axis. One year of field operation data was collected and DHW tapping examples are specifically given for Wednesday 09.01.2019 and Sunday 12.01.2019. Maximum tapping flow was approximately 1,5 m^3/hr and 1,9 m^3/hr, corresponding to an instant DHW capacity of 78 kW and 99 kW. Data's are in general sampled with a resolution of 10 sec, providing detailed insights to the DHW tapping pattern.

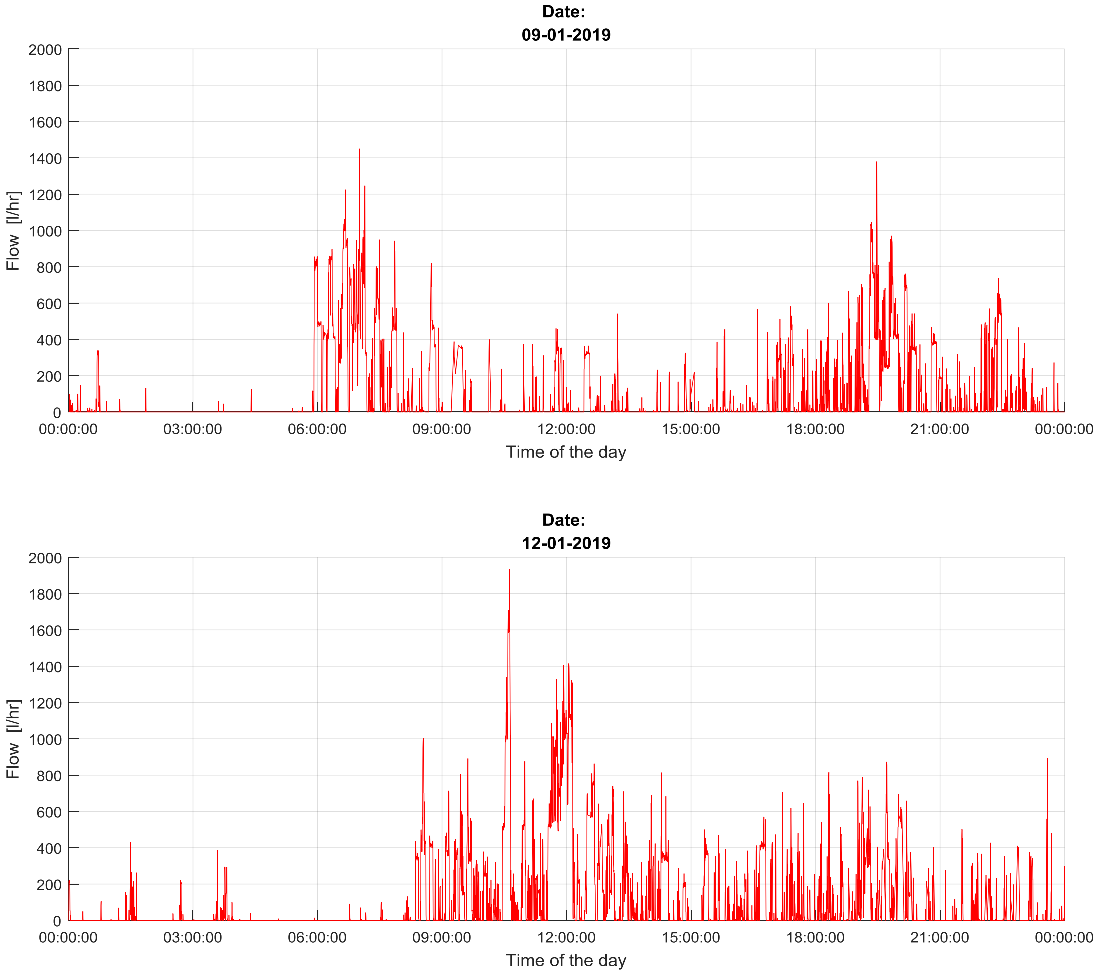

Figure 5: DHW tapped from HBS during the day, two exemplary days, Wednesday 09.01.2019 and Sunday 12.01.2019

It can be seen, that the amount of tapped DHW (at 55°C) from the HBS was on a similar volume for the weekday compared to the weekend day. In this example, for the week day (upper graph) it was 2.312 liters, where it was 2.446 liters (lower graph) in the weekend day. Further, during the weekday the tapping was more concentrated around the morning and evening hours, starting typically at 6o´clock, whereas the tapping was spread out during the weekend day with a later starting time in the morning.

A simple charging control scheme was implemented to ensure hot water at all times, the approach was as follows: In case the tank top temperature falls below 56°C (T tank top #1) charging was initiated and continued until the tank

bottom temperature (T tank #5) was above 50°C. The main heat pump condenser boosts the DH charging temperature from approximately 44°C (T DH flow) to 63°C (T L-HP flow to tank), where the evaporator returns the DH water at a temperature of approximately 24°C (T L-HP return). The tapped DHW is shown as well (Q DHW). During charging of the DH tank, the flow through the condenser was approximately 730 l/hr, whereas the flow through the evaporator was 530 l/hr. DH temperatures in different vertical locations of the tank are shown as T tank top #1 to T tank #5. The charging profile for the HBS for the 12.01.2019 can be seen in

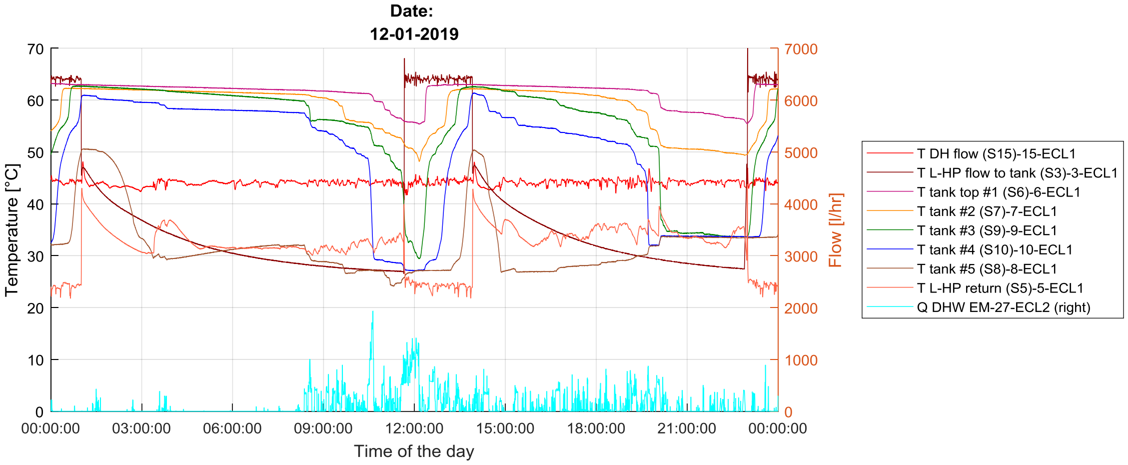

Figure 6. The DH tanks was charged 3 times during this day, until 01:00, then again at around 11:30 to 13:15 and the last charging started at 23:00.

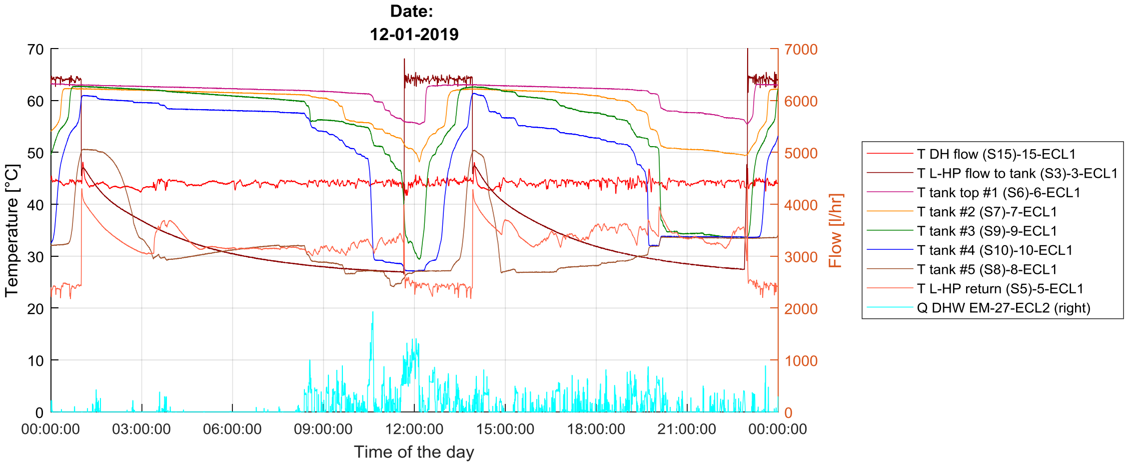

Figure 6: Charging profile of HBS

In periods without charging, the tank temperatures are decreasing during DHW tapping (turquoise line) and in periods with charging the tank temperatures are increasing.

1.6 Basic performance of HBS

In terms of performance, two different types of indicators are presented for the HBS. Specific Coefficient Of Performance (COP) are given for each heat pump respectively, taking into account only the flow of heat and electricity experienced by the heat pumps, i.e. the heat load of the condenser divided by the consumed electricity for compression. An alternative indicator, the daily electricity share evaluates the HBS station in general, in which case the heat supplied by the HBS station to both production of DHW and reheating of DHW circulation is divided by the sum of electricity for the heat pumps. In this case the remaining share is ULTDH.

The main heat pump condenser is boosting the temperature from 44°C to 63°C, at a flow of 730 l/hr. This corresponds to a thermal capacity of 16 kW. With an electric load of approx. 3 kW, it results in a typical COP of 5.4, which was expected for the design condition.

The circulation heat pump condenser was boosting the DHW circulation water from 50°C to 55°C, at a circulation flow of 540 l/hr, corresponding to a capacity of 3.1 kW. With an electric load of approx. 0.6 kW, it results in a typical COP of 5.2, which was expected.

The lower the DHW volume produced by the HBS, the less impact the DH use has on the electric share of the HBS. In case no DHW is produced at all (the tank is not charged, meaning the main HP is not operated), the daily electric share will in principle be one divided by the COP of the circulation HP, say 1/5,2 = 0,19, which can be seen as a trend from Figure 7. At a high DHW volume, say at 2.500 liters/day, the daily electric share is around 12%. At the average daily DHW production volume of 1.700 liters/day, a typical electric share is 14%. In this case the DH share is the remaining 86%.

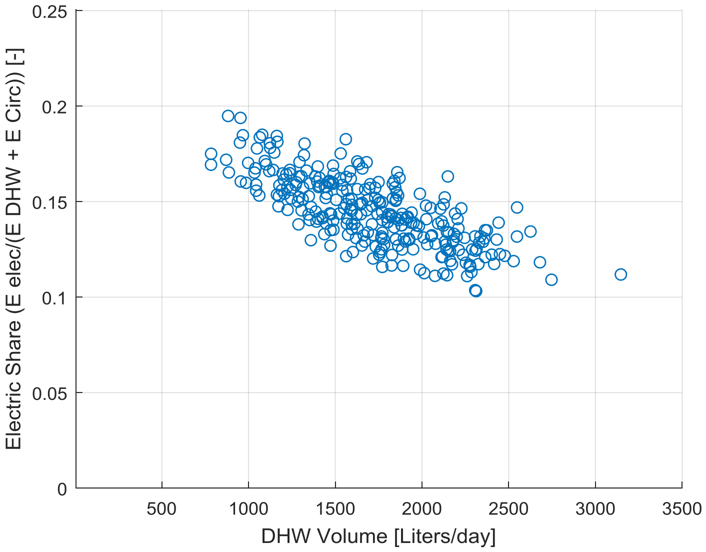

Figure 7: Electric shares of operating the HBS, in dependence of the amount of DHW produced

The data spread on Figure 7 is because the tank is not necessarily charged the same day as the DHW is produced. The data’s shown are pr. day. from midnight to midnight. For this building the energy for producing DHW and the energy for reheating the DHW circulation is on the same level.

1.7 HBS Load Shift Potential, electric and DH

The load shift potential is based on the daily DHW consumption or production, shown in Figure 8. For DHW, the average consumption is 75 kWh/day, at average DHW consumption of 1.700 liters/day, covered by the energy source of electricity and DH (ULTDH). The average electric consumption of the main heat pump is 7 kWh/day, representing the average electric load shift potential. Further, the average DH load shift potential pr. day is the difference of 75-7 kWh = 68 kWh/day. The heating of the DHW circulation by the circulation HP provides no load or fuel shift capacity.

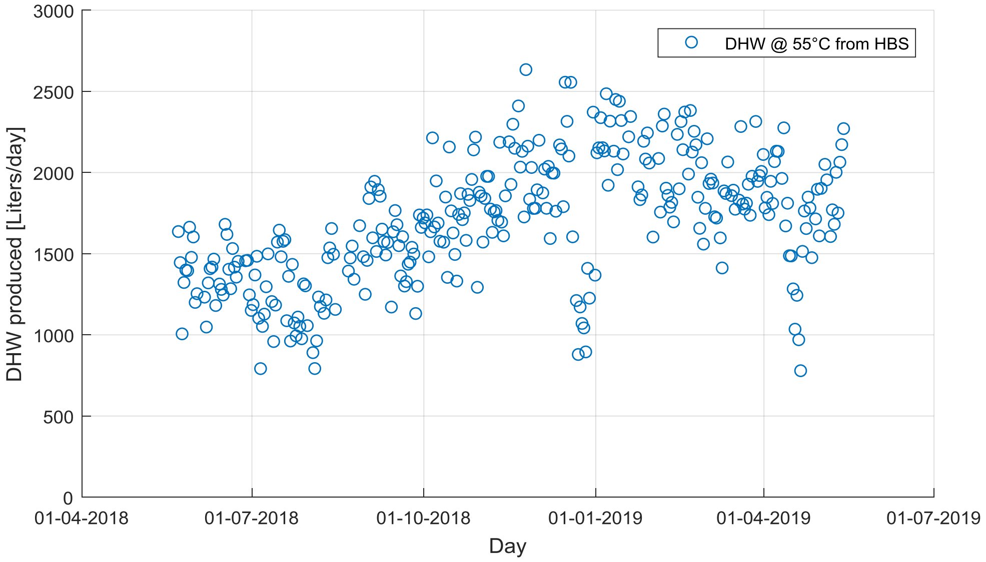

Figure 8: DHW produced by HBS pr. day

The yearly variation of load shift flexibility is dependent on the produced DHW volume and thus the related energy. Assuming a representative low level of DHW volume of 800 liters pr. day and a representative high level of 2.500 liters pr. day, see Figure 9 left graph, then the daily load shift potential as stated above (Elec. 7 kWh and DH 68 kWh) has a yearly variation of approx. +/- 50%. From the right figure, the load shift potential (Elec + DH) during majority of days is in the range 40 - 110 kWh. The potential cannot be utilised fully, e.g. due to limitations in tanks size and DHW draw off, thus the practical range is addressed later in this section.

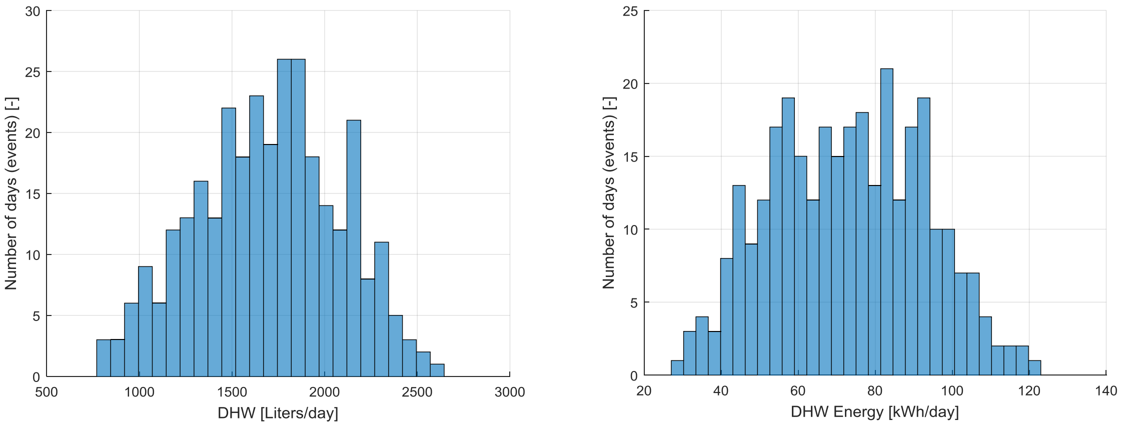

Figure 9: Histogram of DHW volume produced pr. day and DHW energy consumed pr. day

The average consumption of electricity and DH corresponds to a charging duration of approx. 2 hrs. and 20 min. pr. day, where the electric capacity load is approx. 3 kW and the DH capacity load is 30 kW. At a charging flow of 730 l/h the charged volume becomes 1.700 liters, and this corresponds to approx. two charging's of the DH storage tank pr. day. (The full volume of the tank is not utilized due to optimizing the DH return temp from the tank bottom). Considering charging the DH storage tank before the DHW morning peak and before the evening peak, a capacity flexibility of 3 kW electric and 30 kW DH capacity is realized for a period of 1 hr. and 10 min. before the morning peak and before the evening peak in average. The duration period of the load shift varies over the year by approx. +/-50%.

Comparing the DH load shift potential introduced by the HBS to the space heating heat demand pr. day of the building and considering shifting this 5 hrs., the load shift potential for space heating becomes 1,6 kW x 22 flats x 5 hrs = 175 kWh/day at design load condition. The actual load shifting potential of the space heating system will be dependent on the outdoor temperature and hence less reliable and significantly lower than the value indicated at design condition and none outside the heating period. In average the annual load shift potential of the DHW system is expected to be at least in the same range as the heating system.

Regarding fuel shift flexibility, which is obtained by varying the evaporation temperature of the main heat pump, tested in the range from 20°C to 30°C, result in 2 kWh pr. day, thus the electric consumption can vary from 6 to 8 kWh for an average day, with the corresponding DH consumption variation from 69 to 67 kWh/day. The Fuel shift flexibility is regarded as minor.

1.8 DHW forecast model

As input to automatic tank charging scheduling, a forecast algorithm for the DHW draw-off from the central placed HBS is developed and implemented. The forecast is covering a 24-hr time horizon with a resolution of 15 minutes, resulting in 96 slots. The days are distinguished, meaning e.g. a coming Tuesday prediction is based on data from previous Tuesdays, or a coming Saturday prediction is based on data from previous Saturdays. The forecast of the next coming day is then based on a weighting between the forecast and the actual data for the day. And this for each of the time slots during the day. In principle this is a first ordering filtering in the discrete time domain. In case there is a yearly trend, as it can be seen on Figure 8, then this should be compensated to avoid a filtration lag. This is done by first normalising the intraday data by the yearly trend, then use this for calculation of the normalised forecast (first order filtration) and finally calculate the intraday forecast by “de-normalising” the normalised forecast. The actual DHW pr. day, the forecast, the error and the yearly trend can be seen on Figure 10. The weighting factor for the prediction used in this figure is 2/3 weight on the forecast and 1/3 weight on the actual data for forecasting the next coming day.

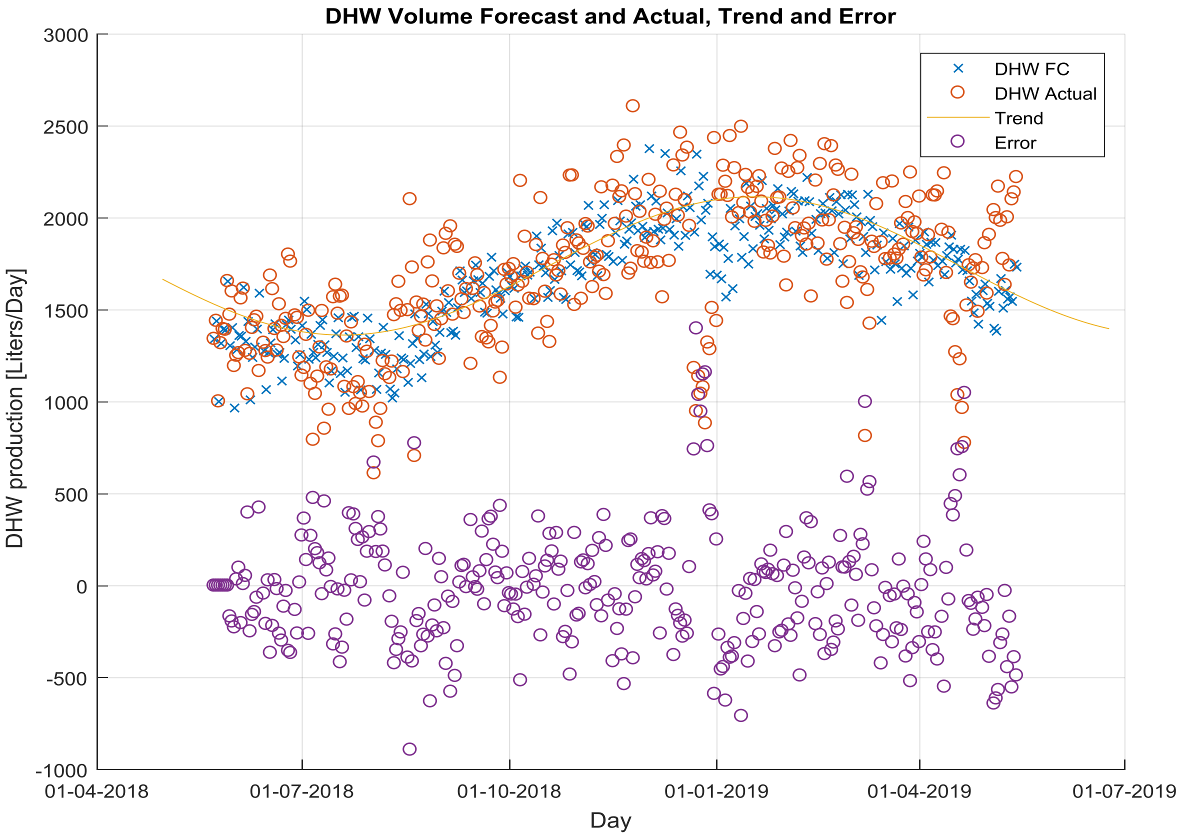

Figure 10: DHW volume pr. day actual, predicted, yearly trend and errors

The trend line is based on a harmonic function with an average value of 1.700 liters/day and an amplitude of 370 liters/day. It can be seen that the forecast is following the yearly trend well, but still with some deviation especially for the last two months of the period. But also, that the forecast is filtered compared to the actual data, since the forecast has less variation around the trend curve compared to the actual data. The first 7 data points are used for “initial” learning, explaining the forecast error is zero those days (calculated with the intention to check the coded algorithms). It can clearly be seen from Figure 10, that the low DHW consumption during the Christmas holiday and during the warm Easter holiday is not well predicted. As an improvement, this behaviour could be implemented in the forecast model going ahead. Some specific examples on intra-day actual and forecast data are shown in Figure 11.

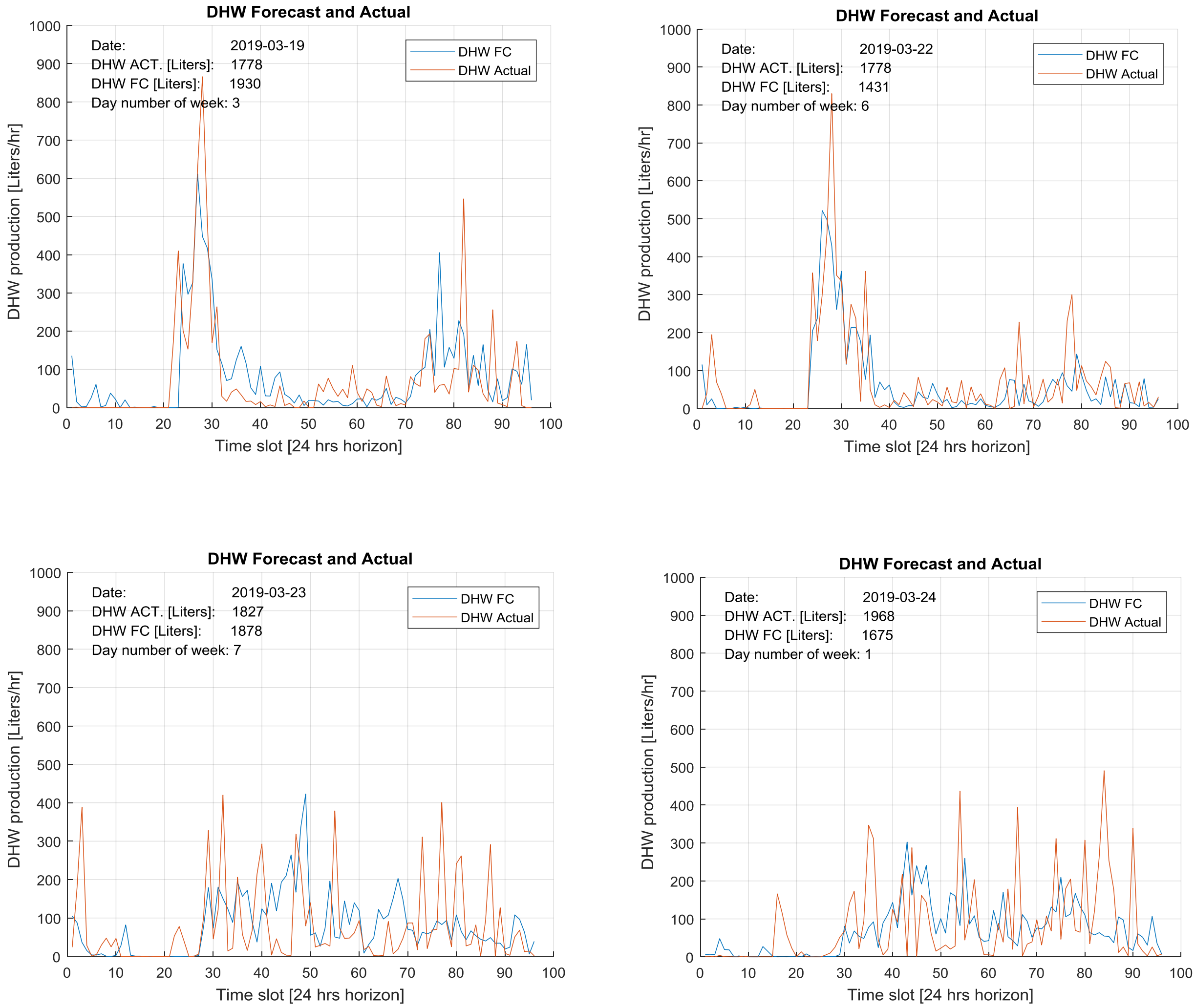

Figure 11: DHW volume intraday actual and predicted for some specific days, where day number 1 is a Sunday, day number 2 is a Monday, and so on.

During the normal week days, the DHW draw-off during the day follows a regular pattern, therefore the forecast is rather good. This is not to the same extend the case for the week-end days or days during holidays. Due to typically non-scheduled activity, the forecast has a higher error level. Day number 1 is a Sunday, day number 2 is a Monday, and so on. Also, from Figure 11the filtering of the forecast compared to the actual data can be seen.

1.9 Automatic scheduling of HBS

Based on the DHW forecast and a dynamic price vector for electricity and DH, represented by a typical yearly marginal DH production price and the forecasted Nord Pool electricity prices, both on hourly basis, a prognosis and economic based scheduling of the HBS charging was implemented. Besides this, the optimization could also be related to CO2 emissions from DH and electricity or by directly avoiding peak load conflicts by a dynamic peak load period signals from DH and electricity. A combination of those is also possible. The optimization considers charging at lowest energy costs, which includes charging at the latest possible time while considering the constrains of min. and max. charging level of the tanks. A typical 24 hr. scenario is shown on Figure 12.

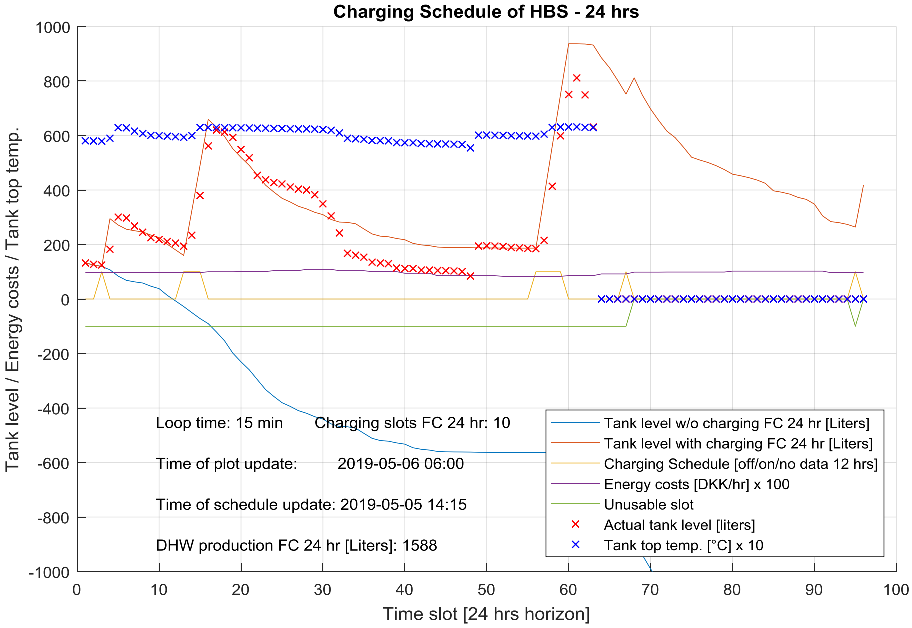

Figure 12: Example of HBS charging schedule, based on prognosis and economic optimisation

For this period, (stating 2019-05-05 14:15), the DHW volume forecast for the next 24 hr. is 1.588 liters. The red curve shows the tank level prediction (volume of usable water above 58°C in the DH tanks), where the red crosses shows the actual tank level. The yellow curve indicates during which slots (duration 15 min) the charging of the tank is active. The magenta line is showing the energy costs for charging the HBS pr. hr. As seen in the figure, the charging is scheduled based on the lowest energy costs, as late as possible and respecting the tank volume constrains (min. and max. charging level). It can further be seen that the tank level is decreasing during periods without charging due to DHW tapping, where its increasing in periods with charging (red line and red crosses). For this 24 hr period, 10 charging slots with a duration of 15 minutes are predicted (slots where the yellow curve has the value = 100, means charging of the HBS. If the yellow curve has the value = 0, no charging is occurring). In case the actual tank level gets below a certain level (50 liters) a new schedule is calculated. Further, in case the prediction error exceeds a specified value (200 liters) a new schedule is calculated, which was happening after slot number 62. The blue crosses are showing the top tank temperature, this for indication only in case of a critical tank temperature level. Further it’s the situation that the marginal DH production prices and Nord Pool electric prices do not result in essential economic gains due to the scheduling, simple because the limited price variations over the day for this example.

1.10 Economic analysis for HBS concept

The possible performance benefit of the ULTDH system has been evaluated in two journal publications as part of the analysis of the HBS concept in WP 10.1. In both cases, the HBS concept was considered as part of an ULTDH system and compared using technical and economic indicators to a state of the art LTDH system.

In the first of the two publications[6], simplified assumptions regarding network and demand profile were used, with characteristics corresponding to the DH network of Aarhusgade in Nordhavn. Two heat production technologies for the

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[6] Ommen T, Thorsen JE, Markussen WB, Elmegaard B. Performance of ultra low temperature district heating systems with utility plant and booster heat pumps, Energy 137, 2017, Pages 544-555, https://doi.org/10.1016/j.energy.2017.05.165

DH networks were considered individually, namely combined heat and power (CHP) and central heat pumps (HPs). By use of the capabilities of the HBS, the return temperature in ULTDH systems was independent of the supply temperature and the heat demand profile, which is not the case for LTDH and older DH generations. However, the return temperature which yields the optimal system performance depends on these characteristics and varies in the considered cases between 21 °C and 27 °C.

When using a central HP to supply the DH system, the resulting coefficient of system performance (COSP) was in the range of 3.9 (-) to 4.7 (-) for equipment with realistic component efficiencies and effectiveness as well as appropriate values for pressure loss and heat loss in the DH system. The COSPs correspond to an improvement of 12 % for the reference case, if the system was supplied by central HPs. However, in case the heat originated from an extraction CHP, the ULTDH system with HBS resulted in a decrease of 20 % in COSP compared to LTDH.

The second publication[7] aimed at analyzing under which conditions ULTDH with the HBS concept could be feasible in terms of levelized cost of heat and socioeconomic net present value compared to LTDH systems for newly developed areas. The overall cost of the system included investment, operation and maintenance and capital cost of all parts of the system, i.e. heat production unit, network, booster HPs, substation. As central heat production units, a range of heat sources for heat pumps and heat recovery solutions were considered. It was systematically assessed how the plot ratio (heated floor area divided by land area) of the supplied area and the DHW share of the total heat demand influence the feasibility of ULTDH systems. It was found that ULTDH systems with HBS benefit from low DHW shares and high plot ratios. The results showed that for ULTDH to be feasible the difference in heat production units needs to be high enough to offset the additional investment cost, as the lower heat losses from the system cannot offset these additional costs alone. This could e.g. be the case if excess heat at temperatures high enough to supply ULTDH directly, e.g. from the return line of an adjacent conventional DH system. In that case, and assuming a plot ratio of 1.48, which is expected for the next development phase of Nordhavn, Levantkaj, the DHW share would have to be around 20% or lower in order for ULDTH to be feasible compared to LTDH. These values do however not correspond to current and future building standards, where the space heating demand has to be low and thus the DHW share is expected to above 50%. The feasible application range may be increased if investment and O&M cost of the HBS can be decreased. Special applications of the HBS system, e.g. retrofitting of existing systems might have a more positive business case, as the DH network investment cost could be avoided. However, these cases were not analyses in this study.

As a third contribution, the possible impact of changed DH tariffs for the users was estimated. The analyzed ULTDH system is able to operate at lower supply temperatures than conventional/LTDH systems and provides the option to control the return temperature, according to the optimal performance of the system. Today, the incentives used by large DH networks to change consumer operation, focus mainly on the reduction of the return temperature, as the forward temperature in all branches of the network must be high enough to supply hot tap water and prevent legionella decease. By use of the HBS, the temperature constraint in distant branches could be reduced in particular areas of the network. The value of reduction in forward and return temperatures in various months of the year is being analyzed in detail in T8.4 but is at the time of writing not concluded. It is expected that the value of changed forward temperature is significantly higher than the corresponding value for the return, as this significantly influences many contributions to the DH price, such as production and source, transmission and distribution. Corresponding changes to the return temperature mainly affect the transmission and distribution cost.

Using the current pricing scheme, the estimation of benefit from operating an HBS can be calculated by the return temperature tariff, as well as the consumption of electricity for the heat pumps. In Copenhagen, the DH supplier

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[7] Meesenburg W, Ommen T, Thorsen JE, Elmegaard B. Economic feasibility of ultra-low temperature district heating systems in newly built areas supplied by renewable energy, submitted to Energy, April 2019

(HOFOR) uses a 0.8% reduction in DH cost per reduced return temperature degree. This is granted for reductions of at least of 5 K more than the average 31 K cooling[8]. For specific consumption characteristics such as the annual heat demand (e.g. 5.2 MWh) per house/flat, the performance characteristics of the HBS (e.g. as presented above), and an assumption regarding the share of the DHW (50%) to the total heat demand, it is possible to calculate the break even in terms of return temperature to satisfy the cost of electricity. For the specific numbers mentioned in parenthesis above, a surplus cooling of approximately 13 K would be sufficient to cover the electricity expenses when considering only running cost. Specifically, in Nordhavn where supply temperatures are approximately 70 ℃, this result in an average return temperature of 26 ℃, which is considered as realistic for a well-operated system. Any improvement in performance of the HBS, or in case of reduced DH tariff from lower supply temperatures, would improve the business case, and allow for some investment. In other parts of the Greater Copenhagen DH system, the return temperature tariff is above 0.8 % per K reduction, which would also improve the possibility for investing in the technology.

1.11 Market estimation for HBS concept

When estimating the market potential for the HBS concept, it should be kept in mind that the specific concept to our knowledge so far only is realised as part of the ELN project. This means the HBS concept is to be understood as "successfully demonstrated" in one location, and thus must be demonstrated in more locations and in higher numbers to get the needed knowledge for a more solid market estimation. Anyhow the HBS concept is part of a general research and demonstration trend within the sector, focusing on boosting the temperature by means of boosters (heat pumps). Both EU funded (H2020, RES-8) and Danish funded (EUDP, IFD) projects have been executed to support this area of research and demonstration.

A "short term rough" market potential estimation for Danfoss could be 5 DH sites times 2 HBS, within the next 3 years as part of research and demonstration projects. Thereafter the market potential will be dependent on the economic feasibility of the concept in each individual case, where also tariff structures will play a major role. Given a development that will increase the number of cases where the economic feasibility is positive compared to LTDH, e.g. utilization of waste heat or return water that has sufficiently high temperature for floor heating, the market potential could become rather large.

The concept of boosting the temperature decentral has attracted high interest at international conferences, where the topic has a growing share of research papers and presentations. Further, DH utilities show increasing interest, both in Denmark and abroad. Here our understanding is that a booster concept is not a main stream product but will need certain boundary conditions to be advantageous compared to "conventional" LTDH as described in 1.10. In relation to the general concept of boosting the temperature decentral by a heat pump, we have apart from DK seen interest from UK, NL, GER, AT and SWE so far. The starting EU funded project (RES-8) REWARDHeat, where Danfoss is a partner, is focusing on decentral heat boosters and involves potential demonstration sites in DK, GER, SWE, IT and CRO.

The HBS concept will be less obvious in old non-renovated buildings, due to the high temperature need of the heating system, but in new buildings with underfloor heating systems it is. For a new urban development area, like Nordhavns Levantkaj, the HBS concept could become relevant. The area could be designed for ULTDH, where the energy input e.g. should be the DH return water from the existing DH system. This temperature is typically in the range 35-45°C, and thus relevant for the HBS concept. Also, where the source of energy for DH is at low temperature level, e.g. solar thermal, geothermal, industry surplus and data centres, the concept of HBS in combination with underfloor heating is relevant to consider.

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[8] https://www.hofor.dk/privat/priser-paa-forsyninger-privatkunder/prisen-paa-fjernvarme-2019-privatkunder/

Finally, the value of the load shift potential, temperature dependent DH energy prices both flow and return and the electric energy prices will determine where the HBS concept is feasible in each individual case going ahead.

1.12 Discussion and future work

Even the HBS runs successfully and an automatic economic and predictive control algorithm is in place and running, the intention is to implement more advanced MPC algorithms, like optimize the main heat pump evaporation temperature, DH tank charging temperature, source for circulation heat pump and a more advanced DHW prediction method. Work is ongoing in this respect, and the realization of tests in the field is straight forward, also because all HW, communication and remote control is up running. Further, more tests on especially fuel shift should be made and evaluated.

1.13 Conclusion on Heat Booster Substation

Based on the experience made (12 months so far), it can be concluded that the HBS unit is successfully installed, tested and operating. The DHW is produced at 55°C, DHW circulation is raised continuously from 50-55°C, with a DH supply temperature of 45°C and a DH return temperature of typically 30°C. The share of electric energy consumption for DHW and DHW circulation service is 14%, at the average produced DHW volume of 1.700 liters pr. day. Whereas the DH share is the remaining 86%. Due to the variation of DHW draw off pr. day over the year, the electric share varies e.g. from 12%, at a produced DHW volume of 2.500 liters pr. day, to 17% at a produced DHW volume of 1.000 liters pr. day. Note that electric share is based on DHW as well as DHW circulation production.

The daily average DHW load shift potential is 75 kWh/day for the 22-flat building, hereof electricity accounts for 7 kWh/day and thus DH accounts for the remaining 67 kWh/day. On a yearly basis it’s at least on the same level as the load shift potential for the heating system of the building. Regarding capacity flexibility, this is 3 kW electric and 30 kW DH realized for e.g. a period of 1 hr. and 10 min. before the morning DHW peak and before the evening DHW peak in average over the year.

Regarding fuel shift flexibility, which is obtained by varying the evaporation temperature of the main heat pump, tested in the range corresponding to a DH return temperature from 20°C to 30°C, this result in 2 kWh pr. day, thus the electric consumption can vary from 6 to 8 kWh for an average day, with the corresponding DH variation from 66 to 68 kWh/day. The Fuel shift flexibility is regarded as minor.

A prognosis and economic based scheduling of the HBS charging is implemented, optimizing for lowest energy costs, latest possible charging among the lowest cost periods and observing the constrains of min. and max. charging level of the tank. By charging the tank as late as possible the heat loss from the tank is reduced due to a lower surface temperature.

A number of feasibility studies has been made for the HBS concept compared to the LTDH concept with different energy sources, showing under the current tariffs system the concept is very limited economically feasible, say only feasible under special system conditions. For a new urban development area, like Nordhavns Levantkaj, the HBS concept could become relevant. This type of area could be designed for ULTDH, where the DH energy input should be the DH return water from the existing DH system. This temperature is typically in the range 35-45°C, and thus relevant for the HBS concept. Still adjustments to the current energy price structures will be needed to make the concept feasible. Also, where the source of energy for DH is at low temperature level, e.g. solar thermal, geothermal, industry surplus and data centres, the concept of HBS in combination with underfloor heating is relevant to consider. Further, the value of the load shift potential, temperature dependent DH energy prices both flow and return and the electric energy prices will determine if the HBS concept is feasible in each individual case.

2. Circulation Booster for Domestic Hot Water

2.1 Introduction

As part of the Energylab Nordhavn project, Danfoss has installed a Circulation Booster (CB) in a multifamily house located at Strandboulevarden 3, close to the Nordhavn Area. The installation was made December 2018. The purpose of the CB is to boost the DHW circulation water from 50°C to 55°C, and at the same time securing a low DH return temperature from this part of the service. Especially in buildings where the DHW circulation loss is high compared to the DHW draw off, it's a challenge to realise a low DH return temperature by direct heat exchange, due to the high share of DHW circulation return water at 50°C. The CB concept is a promising concept in this regard. A low DH return temperature is a precondition for reducing the DH flow temperature to appropriate levels, which is one of the characteristics of the 4th generation DH.

2.2 The field site building – Circulation Booster at Strandboulevarden

Strandboulevarden 3 is a building from 1902 and includes 15 spacious apartments. Characteristic for this building is the high DHW circulation loss relatively to the DHW draw off, which is not uncommon for old multifamily buildings. In this case the DHW circulation loss accounts for around 70% of the total energy use for DHW draw off and circulation.

Figure 13: The building at Strandboulevarden 3, where the CB is installed

The CB is installed in the technical room in the basement of the building and is connected to the existing DHW system in a flexible way, giving the opportunity for easy switch back to the original installed system concept, see Figure 14.

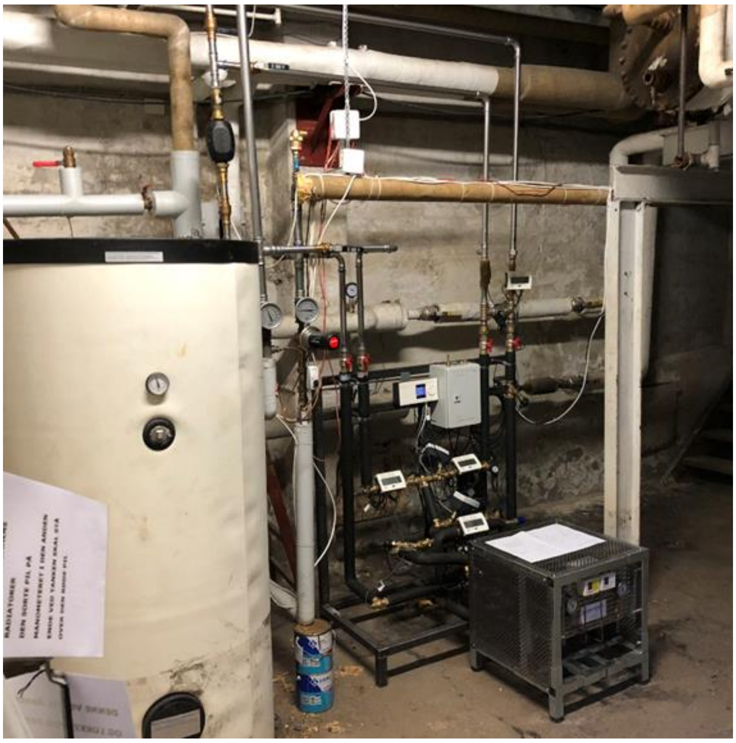

Figure 14: CB installed in technical room at strandboulevarden 3

The heat pump can be seen in the lower right corner of the figure. The meters, control valves, pump, electric cabinet and controller can be seen behind the heat pump. The existing DHW tank appears in the left side of the figure.

2.3 Circulation Booster layout

The basic principle of the CB can be seen in Figure 15, where only the main components are shown for simplicity. The energy transferred to heat up the DHW circulation from 50-55°C is applied in two steps. The return water from the DHW circulation system is first heated by the heat pump condenser and in the second step by direct heat exchange. The source of energy for the second step is DH, where the direct heat exchange heats up the DHW circulation to 55°C and cools down the DH to approx. 53°C. In this way the DH is cooled down to the extent possible by direct heat exchange. The DH water at 53°C is as well the energy source for the heat pump evaporator, and the heat pump is cooling the DH water down to 20-25°C, while it heats up the DHW circulation water from 50°C to approx. 53-54°C.

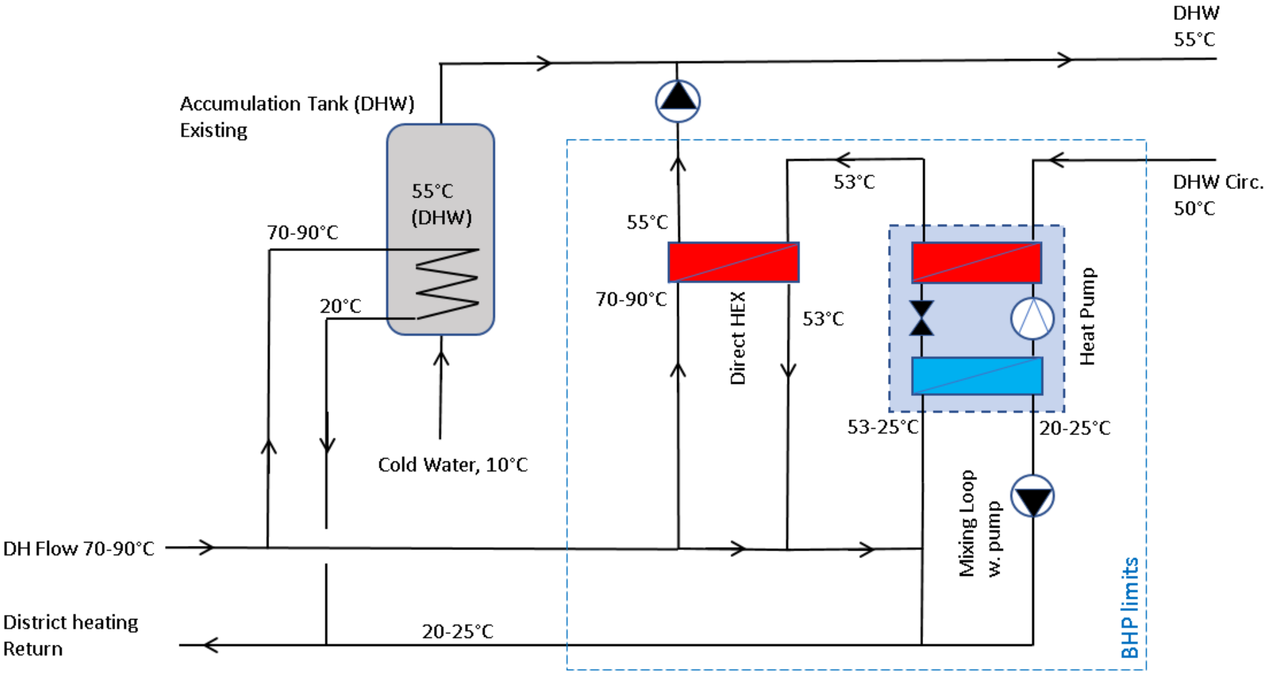

Figure 15: The basic principle of the Circulation Booster

By introducing this two-step concept, the capacity of the heat pump can be reduced (the direct heat exchange covers a part of the needed capacity) and subsequently the electric consumption is reduced. The capacity split between the direct heat exchange and the heat pump gives the trade-off between the reduction of the DH return temperature and the electric consumption of the heat pump. The heat pump control is based on constant speed operation, i.e. the capacity control is limited to be based on varying the evaporation temperature of the heat pump. This is done by adjusting the DH evaporator inlet temperature by means of the mixing loop. Under normal operation no DH flow is bypassing the direct heat exchange.

2.4 Circulation Booster basic operation

The basic operation of the CB is presented by field operational data in the following graphs.

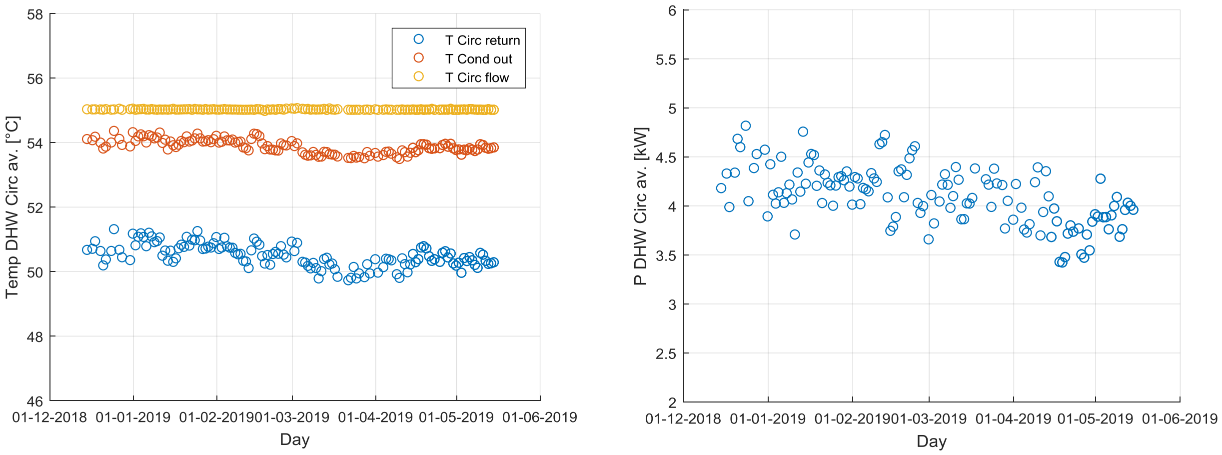

Figure 16: DHW circulation temperatures and heat flow rate

From Figure 16 (left), it can be seen that DHW circulation average return temperature pr. day is a bit higher than 50°C, which is related to the situation that the circulation flow is constant (and in principle a bit too high) and not as usually temperature controlled. Anyhow, this has very limited impact on the analysis and results. The DHW circulation flow temperature is 55 °C as set on the controller. Based on the intermediate temperature between the heat pump and the direct heat exchanger it can be seen that the heat pump has the greater share of the energy input to the DHW circulation, as the mass flow of circulated water is equal through the two technologies. The average heat flow rate required to maintain DHW circulation temperatures are seen in the figure to the right, typically 4.2 kW, but varying from 3.7 kW to 4.8 kW, influenced by the DHW draw-off volume which is explaining the variation. In a situation with high DHW draw-off volume, less energy is needed from the CB to maintain the DHW circulation temperatures. The ambient temperature has a minor impact on the DHW energy as well. This variation is handled by the heat power from the direct heat exchanger mainly, and to a smaller and indirect part the heat power of the HP.

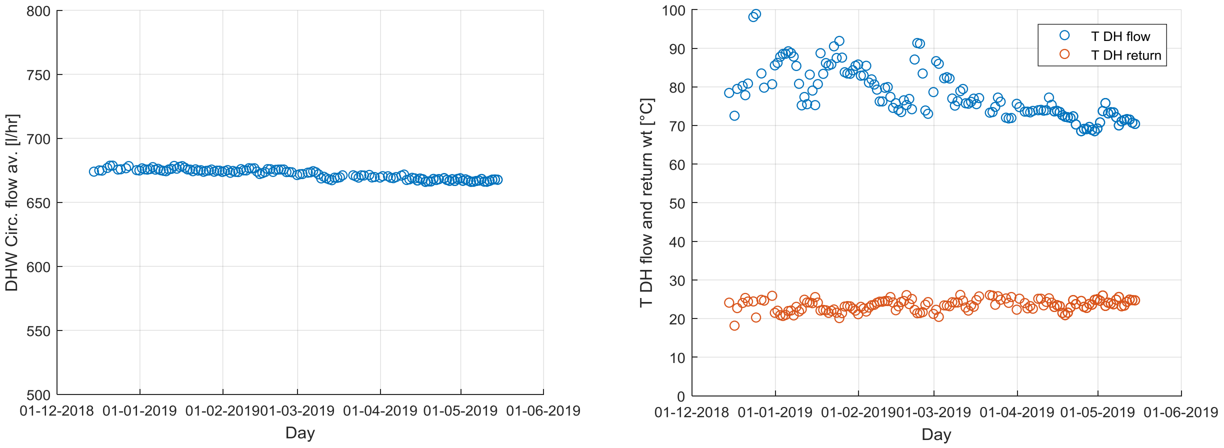

Figure 17: DHW circulation flow and DH temperatures

The DHW circulation flow is around 675 liters/hr in average, and as mentioned above constant. The DH flow temperatures is varying over the year and is mainly dependent on the ambient temperature. The DH return temperature from the CB is in the range 20-25°C, see Figure 17.

2.5 Performance of the Circulation Booster

The main parameter influencing the performance of the CB is the DH flow temperature. Therefore, the following figures are using this parameter as x-axis. The circulation heat flow rate is weakly dependent on the ambient temperature and therefore also weakly dependent on the DH forward temperature, since those are typically linked, see Figure 18 (left). Also in this case the data spread is related to the varying amount of tapped DHW over time, influencing the needed energy input from the CB.

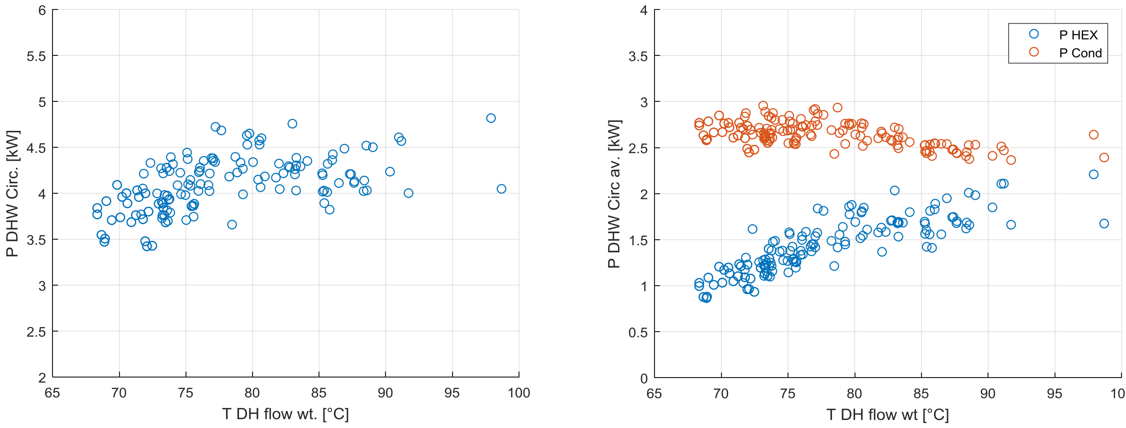

Figure 18: DHW circulation heat power total and split into direct heat exchange (HEX) and condenser

The split between the heat power input from the direct heat exchange and the condenser is shown in the right figure. At increasing DH flow temperatures, the direct heat exchange increases and the condenser heat power decreases. This is because the evaporation temperature decreases at increasing DH flow temperature due to the lower DH flow through the evaporator, see Figure 19, and thus results in a lower heat pump capacity. The direct heat exchanger adjusts to maintain 55°C DHW flow temperature.

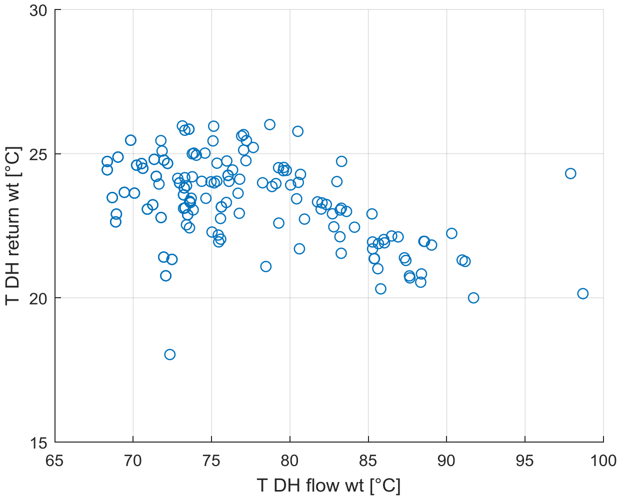

**Figure 19:	DH return temperature dependency of DH flow temperature**

A higher DH flow temperature results in a lower heat pump capacity, and thus a lower electric consumption, resulting in a decreased electric share for the service, see Figure 20. The electric share is the relation between electric energy consumption for the heat pump and the DHW circulation heat input, both the direct heat exchange and the heat pump. The electric share is in the range from 15 to 20% and is mainly dependent on the DH flow temperature.

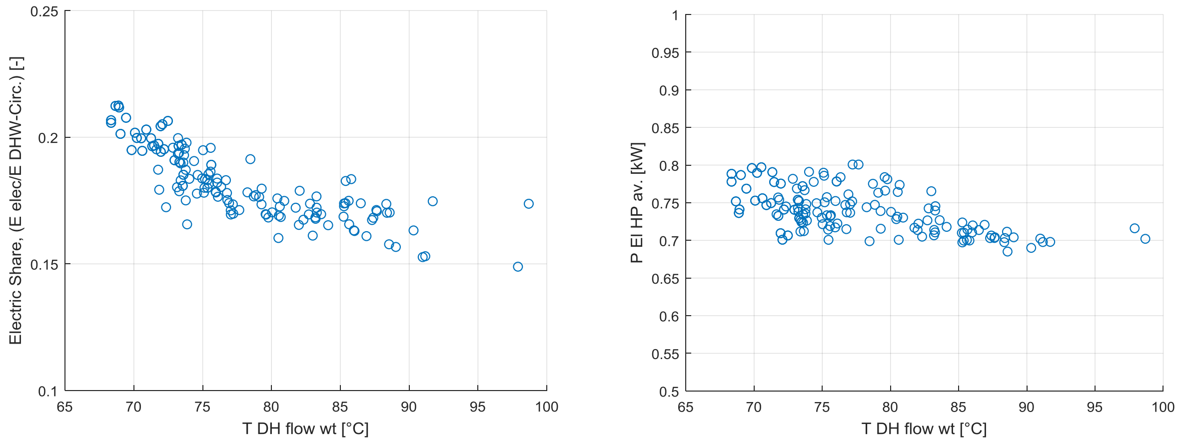

Figure 20: Electric share and consumption for the Circulation Booster

It can as well be seen (right figure) that the electric power for the heat pump varies from 0,7 to 0,8 kW in average pr. day.

A representative DH flow temperature is 80°C. At this condition the electric share is 17% with a DH return temperature from the CB at 23°C.

2.6 Performance of DHW system, Initial and with Circulation Booster

A comparative study of the performance of the DHW system between the case before and after installing the CB has been carried out choosing two representative time periods for each scenario, both with the same length of 19 days. The same period applies for the economic analysis in Chapter 2.7.

Table 1. Performance of DHW system comparison, initial and with CB

	Without CB	With CB
Time period	09/10/2018 - 27/10/2018	09/01/2019 - 27/01/2019
DH for DHW tank Without CB (DHW prod. + DHW Circ.) With CB (DHW prod.) Energy consumption (kWh)	2660	1054
DH for DHW tank: Without CB (DHW prod. + DHW Circ.) With CB (DHW prod.) DH water consumption (m^3)	70	13
DH for CB (DHW circ.) DH Energy consumption (kWh)	-	1577
DH for CB (DHW circ.) DH water consumption (m^3)	-	23
Total DH for DHW (DHW prod. + DHW circ.) DH energy consumption (kWh)	2660	2631
Total DH for DHW (DHW prod. + DHW circ.) DH water consumption (m^3)	70	36
Average DH T flow (°C)	78	80,5
Average DH T return (°C)	45,5	18
Average DH ΔT (°C) for DHW (DHW prod. + DHW circ.)	32.5	62.5

HP Electricity consumption (kWh)	-	355
Total Energy consumption (kWh)	**2660**	**2987**
Circulation heat loss (kWh)	1978	1932
Cold water energy consumption (kWh)	682	1018
Cold water volume consumption (m^3)	15	19

As it can be seen in *Table **1***, the Total DH for DHW (DHW prod. + DHW circ.) in both scenarios is almost the same (1% difference). Regarding the electrical energy consumption of the heat pump, if a thermal loss of 30% of the electric consumption is assumed, and with a calculated average electrical power of 0.73 kW during the period, the total heat capacity loss in the period is: 0.73 kW · 19 days · 24 h/day · 0.3 = 100 kWh (heat loss from the compressor, which cannot be insulated due to cooling demands). Therefore, the total energy consumption has increased by 8.5% in the scenario with CB or in absolute terms by 227 kWh, (2987-2660-100=227 kWh). This seems to indicate that the DWH consumption in the period with CB is higher, and this is also shown by the higher cold-water energy and volume consumption. Indeed, the cold-water volume consumption in the second period is 27% higher. As a matter of fact, the same seasonal influence can be seen for the case of Havnehuset, where the increase of consumption is around 29% for the same period (see Figure 8). Furthermore, a smaller part of the increase is related to the higher DHW circulation heat loss due to the ambient temperature, see Figure 18.

Moreover, the average DH ΔT (ºC) for DHW almost doubles (from 32.5ºC to 62.5ºC) with CB. This shows the potential of the new system to reduce the DH return temperature, in this example from 45,5 to 18°C. This variation of temperature difference plays a major role in the economic cooling correction or bonus as it will be shown in the next chapter.

2.7 Economic analysis for Circulation Booster

Some parameters were varied to see what their impact is for the final cost of operation and to conclude if any scenario could make the option with the CB economically more viable than the reference. Table 2 shows the current situation. A cost comparison between both cases has been carried out for the current (and other) scenarios to evaluate the CB economic feasibility. The price for DH has been assumed constant of 0.675 kr./kWh and was taken from HOFOR website[9], (considering taxes and without considering the fixed price (Effektbetaling)). For the cooling correction (cooling penalty or reward system), the HOFOR standards have been applied. The average DH ΔT used, is as stated in Table 1, and it has been assumed that the values obtained from the respective periods will represent the annual averaged value. A dead band for the average DH for ΔT from 26ºC to 36ºC does not give any penalty or reward. Below 26ºC a penalty is imposed, while above 36ºC a reward is given. The correction price represents 0.8% of the price for DH (5.4 kr./MWh/ºC). The price for electricity has been assumed a fixed price of 2.15 kr./kWh[10].

Table 2. Cost comparison in current scenario (scenario 0)

	Without CB	With CB
Time period	09/10/2018 - 27/10/2018	09/01/2019 - 27/01/2019
DH for DHW cost (kr.)	1795	1776
Cooling correction (kr.)	0	-376
Electricity cost (kr.)	-	764
Absolute Total Cost (kr.)	**1795**	**2164**
Specific Total Cost (kr./kWh)	**0.67**	**0.73**

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[9] https://www.hofor.dk/privat/priser-paa-forsyninger-privatkunder/prisen-paa-fjernvarme-2019-privatkunder/

[10] http://elpris.dk/#/

As it can be seen, the absolute total running cost with CB is 21% more expensive than without it. However, since the DHW consumption in the second period is significantly higher, the following formula has been used to obtain a cost that is comparable for both periods:

Specific Total Cost (kr./kWh) = Total Cost (Kr.) / (Circulation heat loss + Cold water energy consumption) (kWh)

Using this formula, the relative total cost with CB is 9% more expensive.

Regarding the cooling correction, while in the case without CB, no reward (or penalty) was applied, it provided a reduction of the total cost of 15% in the scenario with CB. This potential of the cooling correction in reducing the total cost has led the study to explore possible new scenarios with a change in the cooling correction regulation. A final scenario with a reduction of the electricity price has also been carried out to see its impact on the economic feasibility of the CB concept.

Table 3. Cost comparison in scenario 1

	Without CB	With CB
Time period	09/10/2018 - 27/10/2018	09/01/2019 - 27/01/2019
DH for DHW cost (kr.)	1795	1776
Cooling correction (kr.)	0	-940
Electricity cost (kr.)	-	764
Total Cost (kr.)	**1795**	**1600**
Specific Total Cost (kr./kWh)	**0.67**	**0.54**

In the first scenario**,** Table 3, the cooling correction unit price represents 2% (instead of the current 0.8%) of the DH cost. Therefore, instead of 5.4 kr./MWh/°C it is assumed 13.5 kr./MWh/°C.
As it can be seen, this change has a huge impact on the cooling correction, which has increased 2.5 times. The specific total cost has been reduced from scenario 0 by 26%, making the option with CB 19% cheaper than without it

Table 4. Cost comparison in scenario 2

	Without CB	With CB
Time period	09/10/2018 - 27/10/2018	09/01/2019 - 27/01/2019
DH for DHW cost (kr.)	1795	1776
Cooling correction (kr.)	-21	-447
Electricity cost (kr.)	-	764
Total Cost (kr.)	**1774**	**2093**
Specific Total Cost (kr./kWh)	**0.67**	**0.71**

In the second scenario, Table 4, the cooling correction applies without a dead band of 10ºC. If the average DH ΔT(ºC)>31ºC a reward is given and if ΔT<31ºC a penalty is applied. This situation slightly increases the cooling correction (19%) compared to scenario 0. Therefore, the final impact is quite limited and the case with CB remains 6% more expensive. It can also be seen, that the cooling reward for the case without CB is minimal, since the temperature difference is only slightly above 31ºC.

Table 5. Cost comparison in scenario 3

	Without CB	With CB
Time period	09/10/2018 - 27/10/2018	09/01/2019 - 27/01/2019
DH for DHW cost (kr.)	1795	1776
Cooling correction (kr.)	-53	-1118
Electricity cost (kr.)	-	764

Total Cost (kr.)	**1742**	**1422**
Specific Total Cost (kr./kWh)	**0.65**	**0.48**

The scenario 3, Table 5, is a combination of scenario 1 and 2, applying both changes at the same time. As expected, since this scenario combines the positive effect on the case with CB, the cooling correction is almost 3 times greater and it reduces the relative total cost by 34% compared to scenario 0. Therefore, having a CB is 26% cheaper for this scenario. The situation of a cooling correction saving in the magnitude of 60% of the DH energy costs seems very high, and only possible for the DH utility under special conditions.

Table 6. Cost comparison in scenario 4 (with 30% electricity price reduction)

	Without CB	With CB
Time period	09/10/2018 - 27/10/2018	09/01/2019 - 27/01/2019
DH for DHW cost (kr.)	1795	1776
Cooling correction (kr.)	0	-376
Electricity cost (kr.)	-	535
Total Cost (kr.)	**1795**	**1935**
Specific Total Cost (kr./kWh)	**0.67**	**0.66**

Finally, in the last scenario, Table 6, the price of electricity varies, simulating a future scenario with a decrease of the electricity price. In order for the CB option to start being cheaper (in terms of specific total cost), the electricity price should decrease by 30% (i.e. 1.51 kr./kWh compared to the 2.15 kr./kWh in scenario 0).

Considering only the favourable scenarios for the CB so far (scenarios 1, 3 and 4), if the cost of the CB components (17.300 kr.) and installation costs (7.650 kr.) are considered and the results from the analysed periods are extrapolated over the year*, the following results can be obtained.

Table 7. Predicted annual savings and direct payback period with the CB

	Scenario 1	Scenario 3	Scenario 4
Annual savings (kr./year)	6406	8377	493
Payback period	3 years 11 months	3 years	50 years 6 months

**In order to extrapolate the results, an average total energy consumption per day of 135 kWh/day has been chosen.*

The obtained payback period for scenario 4 is not reliable since the assumption of the current DH and electricity prices remaining constant in such a long period of time is just unrealistic. However, for the other two scenarios, the payback period is around 4 and 3 years (for scenario 1 and 3 respectively) and appears acceptable, also seen in the perspective of a CB estimated lifetime of 15 years. A factor to be considered is the economy of scale. An industrialised CB will costs less and thus give a more favourable economic outcome.

2.8 Market estimation for Circulation Booster concept

The CB concept is intended for multifamily houses where the relative DHW circulation energy loss is high compared to the energy for producing the DHW. This is the case in many older buildings where the DHW circulation loss can be up to 85% of the energy for DHW service (DHW production and DHW circulation), in newer buildings this value is typically up to 50%, and thus the benefits of the CB is reduced, but might still be relevant depending on other factors such as DH costs, DH return temperature bonus schemes and electric energy costs.

A “short term rough” market potential estimation could be 5 DH sites times 10 CB, within the next 3 years as part of demonstration projects. Thereafter the market potential will be dependent on the economic feasibility of the concept in each individual case.

The CB concept is not based on boundary conditions such as ULTDH or underfloor heating which is the case for the HBS. Therefore DH systems as they typically are present can be addressed with the CB concept. Also the CB concept it’s to our knowledge only tested as part of the EnergyLabNordhavn project at one site. More field tests must be made to be able to estimate the market potential in more details. Anyhow, if the value of reducing the DH return temperature is sufficiently high, then the market potential for this concept is huge, both in existing old buildings but potentially also in new buildings, both in Denmark and abroad. The concept thus has significant export potential. A DHW circulation system is a needed boundary condition, and this is typically the case for old buildings and mostly the case for new buildings. A part of the new buildings are equipped with the flat station concept, meaning producing DHW on individual flat level, and thus there is no DHW circulation system to be serviced by the CB concept.

2.9 Discussion and future work

One area of future work could be in relation to optimize the balancing of the heat input from the heat pump and the direct heat exchanger to the DHW circulation more smart. This with the aim to realise fuel shift service (electricity and DH), e.g. by a compressor with variable speed. Further to develop the related automatic control algorithms, based on variable energy costs, to make the control intelligent and smart.

2.10 Conclusion on Circulation Booster for DHW circulation

Based on the experience made (6 months so far), it can be concluded that the CB is successfully installed, tested and operating. The DHW circulation is boosted continuously from 50-55°C, with a DH supply temperature in the range from 70-100°C. The DH return temperature is reduced from a level of approx. 45°C to approx. 20°C for the DHW service (DHW preparation and DHW circulation). The share of electric energy consumption for the CB concept is 17% at a representative DH flow temperature of 80°C. The representative DH return temperature from the CB is 23°C (DHW service). Within the range of DH flow temperatures 70 – 100°C, the electric share is in the range 20- 15% of the energy needed to boost the DHW circulation. The remaining energy source is DH, with a share of 80 – 85%.

Load shift is not possible for this concept, since the CB is running continuously, and energy storage devices are not obvious for this concept.

Fuel shift is possible, to a minor degree, realized by influencing the condenser outlet temperature, and thus influencing the balance of heat from the condenser and the direct heat exchange. No tests are so far made in this regard.

A number of economic scenarios have been made, focussing on different bonus structures related to reduced DH return temperature and electric energy costs. The current tariff structure does not give a feasible economic case for the CB concept. But considering a more progressive bonus scheme for providing a low DH return temperature, the market potential could be interesting in the segment of existing buildings and partly also new buildings with DHW circulation systems. This is also supported by having the simple retrofit demands in mind and driven by the argument that a low DH return temperature is the precondition for a low DH flow temperature, which is one of the characteristics of the 4th generation DH concept.