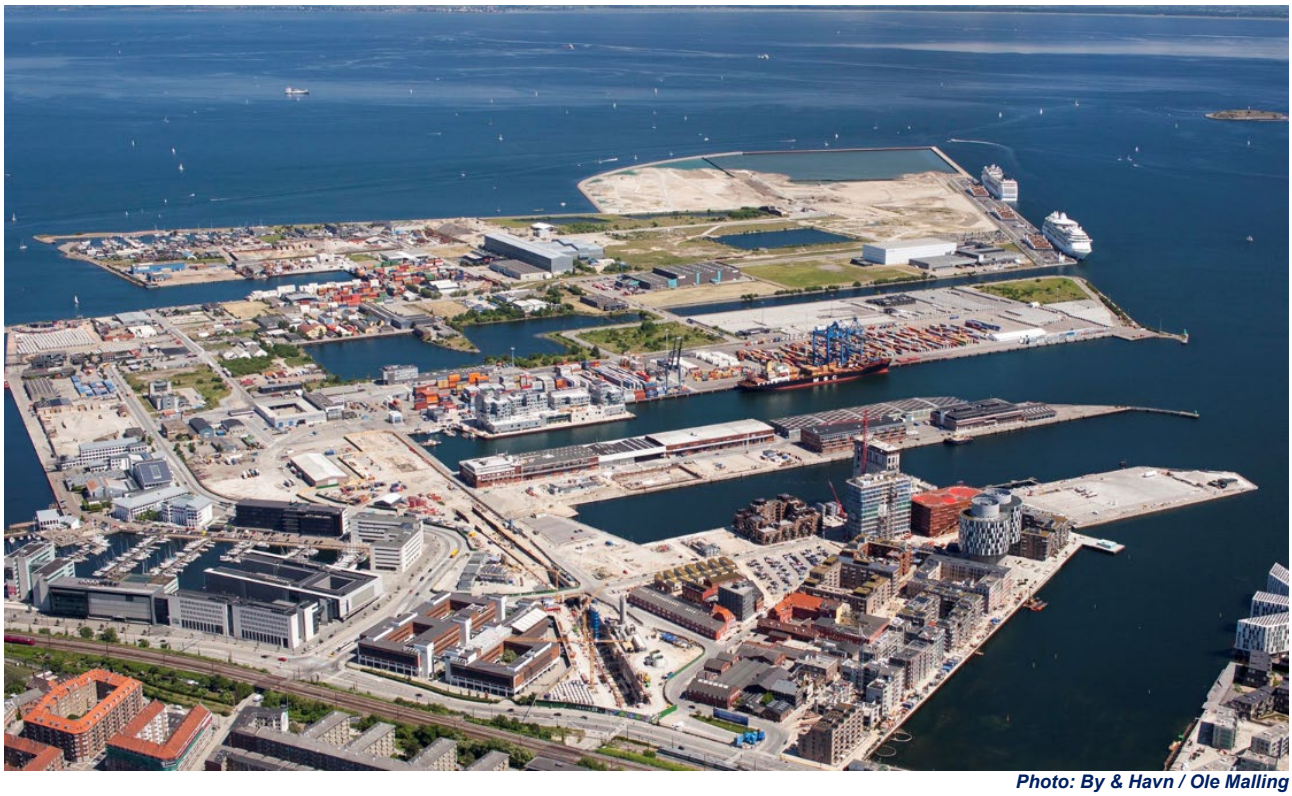
Delivery no.:
WP5.3 – Protocol for intelligent management of heat accumulators



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Date [12-11-2019]

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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.

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Table of Contents

List of Abbreviations

- HA: Heat accumulator
- COP: Coefficient Of Performance
- PSO: Public Service Obligation
- TSO: Transmission System Operator
- DSO: Distribution System Operator

Executive Summary

This deliverable examines the potential of operating a hot water storage tank for district heating optimally with a case-study of a 4,5 MWh tank connected to an island heating grid supplied by a heat pump, commissioned in May 2018.

The aim is to optimize the flexibility provided by the tank for the production units to lower the overall heat costs by smart trading on the electricity markets. This is show cased by modelling and optimizing for the year 2018 and performing verifying tests at the facility to support the modelling framework.

Results indicate that 12,7 % of the total heat costs can be lowered due to intelligent storage management by procuring lower electricity prices (6 %) and participation in the ancillary service market (6,7 %).

These results are compared to a heat accumulator (HA) in the district heating grid of Copenhagen accounting for 3.450 MWh of heat storage, and it is suggested that if the HA capacity was tripled, an annual reduction of 70 - 155 Mio. DKK in heat costs could be provided without considering investment costs. If investment costs are considered, the sensitivities indicate that stronger price signals are required to make it worthwhile to invest in over-sized production capacity to harvest the flexibility potential.

This study thus examines the potential for Copenhagen to invest in larger HA capacity to harvest the potential benefits of operating electricity-driven heat production units intelligently on the electricity markets.

Version Control

Version	Date	Author	Description of Changes
[Official versions only]	[yyyy-mm-dd]		
1a	22-02-2019	Tore	Initial draft
1b	21-08-2019	Tore	Revised version
2	22-08-2019	Kristian	Comments
3	22-08-2019	Tore	Revised version
4	2019-09-11	Brian	Review
5	2019-09-23	Tore & Wiebke	Final revision
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Quality Assurance

Author	Reviewer	Approver
Tore G. Kjeld, HOFOR & Wiebke Meesenburg, Mechanical Engineering	Brian Elmegaard, DTU Mechanical Engineering	WPL group

Status of deliverable		
Action	**By**	**Date/Initials**
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Acknowledgements

The work presented in this deliverable has been performed in close cooperation with Wiebke Meesenburg from DTU Mechanical Engineering. Here, Wiebke has been an integral part of the test program and assisted with the development of the FlexHeat module. This includes tests to improve COP-curves, stratified storage model, start-up costs, and thorough examination of the flexibility potential of a large-scale ammonia heat pump.

1. Introduction

1.1 Purpose

WP5.3 is focused on examining how to use heat accumulators to optimize the operation of heat supply units supplying a district heating network. In this context, heat storages may fulfill different functions, e.g.

a) Balancing production and consumption
b) Optimization of heat supply and electricity usage

a) refers to balancing the forecast error of production units to make sure that the production equals consumption. In b), the storage flexibility is used to lower the heat production costs –either by avoiding the use of peak-load boilers or by providing flexibility with regard to the operation of CHP's, so that they can gain an advantage on the electricity-related markets. This may either be the day-ahead electricity market, the balancing market or the ancillary services market.
In this deliverable, the focus is on an island district heating grid with four customers, which are supplied by a flexible production unit consisting of a heat pump, electric boiler, and a hot water storage tank. This system is used as case-example of intelligent operation of large-scale storage tanks. The expected outcome are suggestions on how to optimize the usage of larger-scale storage tanks in the Greater Copenhagen district heating area.

1.2 System description

The examined facility is named FlexHeat Nordhavn and is part of the island district heating grid depicted in Figure 1. It was designed to supply heat to the system with a high flexibility in terms of heat load, supply temperatures and operation of the heat pump and electric boiler.

Figure 1: The island heating grid in outer Nordhavn, Copenhagen supplying three cruise-ship terminals and the UNICEF warehouse

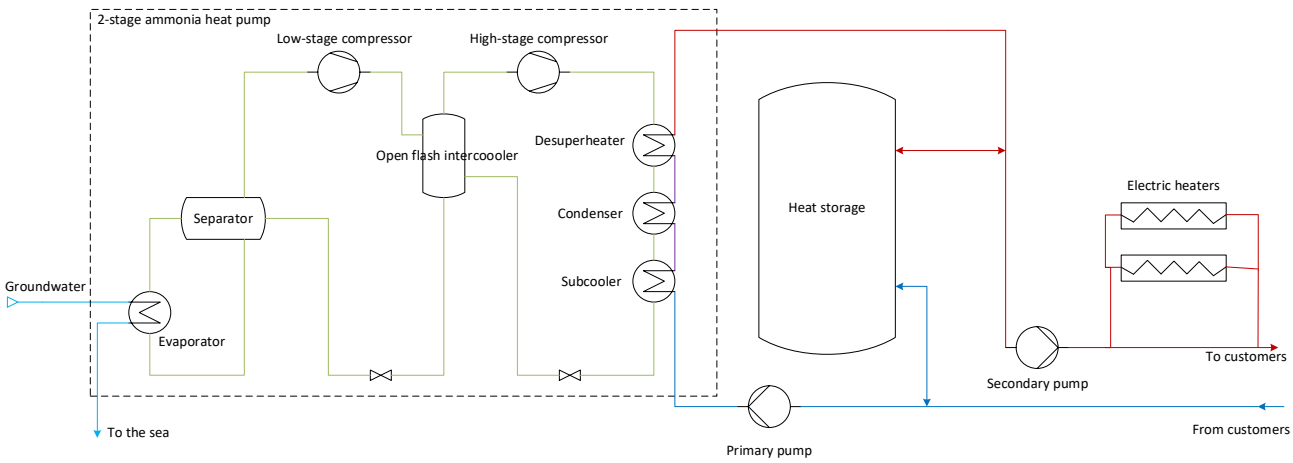


Figure 2: Sketch of the heat pump set up and integration with storage tank and electric heaters in the FlexHeat system. Source: Wiebke Meesenburg, DTU Mechanical Engineering

FlexHeat is responsible for supplying heat to the buildings for space heating and domestic hot water usage. The FlexHeat system is presented in more detail in Figure 2. It has the following specifications:

- Heat pump technology: Two-stage ammonia heat pump using piston compressors.
- Heat pump source: Brackish ground-water (10,5 °C)

- Fullload heat capacity of the heat pump: 800 kJ/s, the load may be varied between ca. 34 % and 100 % fullload, supply temperatures may be adjusted to be between 60-84 °C
- Storage capacity for the HA: 100 m^3 equivalent to 4500 kWh for forward and return temperatures of 75 °C and 35 °C, respectively.
- Electric boiler heating capacity: 200 kJ/s

Two oil boilers are available as back-up if the heat pump is unavailable.

The hot water storage tank is place downstream of the heat pump and upstream of the electric boiler as indicated in Figure 2. This enables the FlexHeat system to run in the following modes:

1. The heat pump runs at a given capacity and based on the consumption level, the remaining heat is delivered into the tank

2. The same as mode 1, but the temperature to the consumers is boosted to a higher level by the electric boilers if this is needed.

3. The heat pump is not running. The storage tank discharges heat to the consumers.

4. Same as in mode 3, but the temperature of the discharged heat from the tank is boosted by the electric boilers to a sufficient level. This is often applied in situations where the temperature in the top of the tank is just below the required temperatures for the customers – and in this case, a small boost from the boilers might be more beneficial than forcing a heat pump start-up if the prices do not match.

5. The heat pump is not running. The return water is circulated through the electric boiler to boost the temperature in the bottom of the tank while discharging the tank.

In all of these modes, the HA has a central position for the system. A more detailed description of the facility and the installation can be found in D5.5a.

1.3 Role of the storage tank

The heat pump in the flexible production unit, FlexHeat, has a minimum load of 34 % and the COP of FlexHeat reaches its highest level at around 80-90 % load. As the heat demand in the system is often lower than the minimum heat pump capacity, a storage tank is necessary to store the additional heat produced during operation and to supply low heat demands. This leads to the first role of the storage tank as mentioned in the purpose:

a) Balancing production and consumption

With a sole focus on balancing production and consumption with the highest possible COP, FlexHeat will run at optimum load until the storage tank reaches its upper storage limit, and then proceeds to discharge until it reaches its lower storage limit. This is a demand-based production pattern. It aims at run the heat pump at the highest possible COP. It does however not take operation cost or fluctuating electricity prices and tariffs into consideration. This leads to the next operation strategy:

b) Market optimization

In the market optimization, the focus is on utilizing the flexibility provided by the storage tank to implement an intelligent schedule, in which the heat pump produces at the lowest cost given the electricity-related markets. In this case heat is produced when electricity prices are low and stored in the tank until the it is consumed. In this strategy, the tank will still be able to help balancing the production and demand and enable the supply of heat demand below the heat pumps' minimum load, as in strategy a).

2. Method

To be able to schedule the operation for FlexHeat according to the two operation strategies two mixed integer linear programming models of the system were developed in Gams. These are presented in the following, with a focus on the modelling of the storage tank.

2.1 Model overview

The model is run with day-ahead prices, taxes and distribution tariffs for 2018. There are two types of simulation horizons:

a) Annual simulation basis
The annual simulation requires a simplified model. The model is based on energy balances for both heat and electricity flows, while the temperature of the heat is disregarded. The model is used for the annual simulation to assess the potential in operating the system intelligently in which the optimization horizon is 8760 hours. Due to the many time-steps, the increasing number of binary constraints in the model means that it is a computational heavy simulation to run. Hence, a more complex model, as later presented in b), would not be able to compute within a reasonable period.

b) Day-to-day operation
For the day-to-day optimization, a more advanced model is used, which includes temperatures and mass flows to more accurately predict the behavior of the system. This optimization is performed every day for the next 48 hours. More advanced constraints can be utilized as the computational burden is significantly lighter.

The models are linear mixed-integer programs, which are solved using the CPLEX-solver. In short, this optimization model applies model predictive control to the system, so the production planning can take future heat demand and electricity prices into account to produce optimally for the current hours. Common for these models is that the system is penalized for every start-up of the heat pump to prevent recurrent cycling of the unit and account for reduced COP during start-up and increased wear. For this model the penalty was set to 30 DKK.

The potential described in this deliverable is based on simulation for 8760 hours in 2018 with model a). Model b) is the day-to-day operation of the site to achieve these monetary savings assessed in model a.

2.1.1 Annual simulation tool

Model a) is evaluated in two specific situations:

i. Simple control loop strategy

This is performed by adapting the site-strategy for running without the smart model, i.e. an autonomous running strategy for the heat pump. Here, the heat pump runs at 88 %, and the strategy is to run the heat pump within the storage boundaries of a lower limit of 0,9 MWh and a higher limit of 4,05 MWh.

Hence, the heat pump continuously charges and discharges depending on the demand level and does not attempt to produce at low electricity prices – this will only occur randomly if it happens. The start-up cost does not influence the pattern in a), but is just an expense that the system is exposed to. Model a) thus reduces to a simple dispatch of the heat pump based on the demand level of the consumers while running at the highest COP.

ii. Intelligent scheduling of the heat pump production

An optimization problem is formulated to minimize the total cost of the system – this is electricity procurement cost and start-up costs. Hence, the system will attempt to produce at the lowest electricity prices while ensuring several consecutive production hours to limit costs on the start-up.

2.1.2 Day-to-day operation module

The day-to-day operation consists of the following modules:

1. Heat demand forecast

2. Forward temperature regression
3. Electricity spot forecast
4. System-specific constraints
    4a) Start-up costs
    4b) Stratified storage model
5. Communication to the SCADA of FlexHeat

This is to have all of the necessary constraints taken into account when performing a day-to-day schedule. The combined module is explained in detail in D5.5b, and thus 1-5 is not described further in this deliverable. However, the modelling of the storage tank in 4b is investigated.

2.2 Modelling of the storage tank

The modelling of the storage tank in the annual simulation (model a) and the day-to-day operation (model b) is quite different. This subsection describes the methodology of modelling the storage tank and the differences.

2.2.1 Annual simulation

The annual simulation model utilizes an input-output energy model of the storage tank.

$$S_{level} = \eta \cdot S_{level(t-1)} - \dot{Q}_{discharge} + \dot{Q}_{charge}$$

Here, the storage level is calculated based on the previous level and the interactions with the storage tank, i.e. charging and discharging of the tank. Here, η, is the storage efficiency, accounting for losses during storage. This loss is examined experimentally by leaving the storage tank charged with no interactions for three consecutive days. Here, the heat loss of the storage tank was assessed to be 0,22 % / hour, hence the applied value for η was $1 - 0.22\ \% = 99.78\ \%$. As temperatures are not taken into account in this model, the represented loss is solely heat loss to the environment.

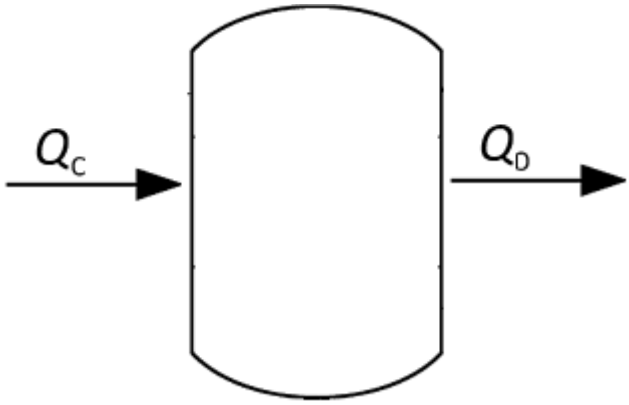


Figure 3: Input-output model for the storage tank.

Figure 3 shows the example of the storage model, which only considers an energy balance.

2.2.2 Day-to-day operation

In the day-to-day operation, temperatures and mass flows are considered. Here, it is necessary to model the temperature development in the tank. Two challenges arise from this:

- Depicting the amount of useful heat
- Modelling the development of temperatures in the tank.

The useful heat is water at significantly high temperatures to be used for district heating – i.e. at temperatures above 60-80 °C depending on the season and demand patterns. The thermocline denotes the layer between the warmer water at the top of the tank and the colder water at the bottom and thereby the amount of useful heat. It is typically characterized by a steep temperature gradient compared to the rest of the tank. The thermocline moves up and down due to discharging and charging respectively and thereby indicates the amount of warm water available. To represent the different temperatures in the tank, a stratified storage model needs to be implemented. In [1], a suggestion for modelling this has been examined for a 52 kWh storage tank – the modelling techniques have been applied here and scaled to FlexHeat.

Assessing the temperature development in the tank requires mass flows in- and out of the tank at given temperatures, which forces a multiplication of temperatures and mass flows. These are non-linearities, which need to be linearized for the MILP optimization problem. Different options how to linearize the resulting equations are given in [1].

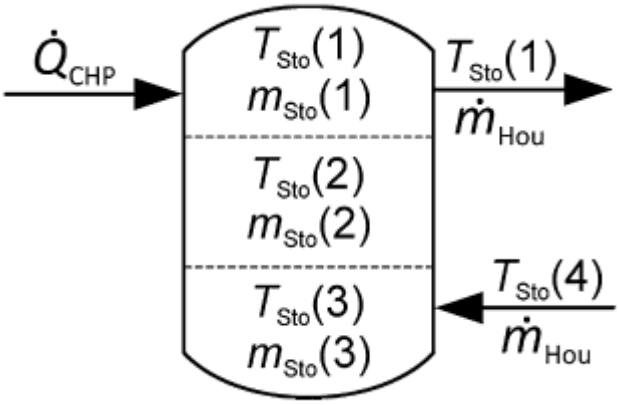


Figure 4: Stratified storage tank example as depicted in [1].

Figure 5 shows how the stratified storage tank is modelled in [1]. it is discretized into three layers. This low amount of layers is also implemented in the FlexHeat model for day-to-day operation, as more layers would increase simulation time more than what would be useful in daily operation.

The following is included in the stratified model:

- Flows in and out of the tank – here the heat is charged from the heat pump at the top of the tank. During discharging, return water enters from the bottom of the tank and hot water is discharged at the top of the tank.
- Heat loss for each layer based on the surface area and on an average heat transfer coefficient for the heat accumulator.
- Interaction between the layers given by a coefficient for transfer between the layers.

In [1], stratified storage parameters are used as presented in Table 1.

Stratified storage parameters.

Layer l	Unit	1	2	3
k_{Sto}	W/(m^2 K)	1.1189	1.1189	1.1189
$A_{Sto}(l)$	m^2	1.8084	1.3666	1.8084
Δz	m	0.5800	0.5800	0.5800
A_{CS}	m^2	0.4418	0.4418	0.4418
κ	W/(m K)	0.6500	0.6500	0.6500
$m_{Sto}(l)$	kg	250.00	250.00	250.00

Table 1: Stratified storage parameters as used in [1].

The dimensions, i.e. height (ΔZ), surface area ($A_{Sto(l)}$), cross-section area (A_{CS}) and mass in the storage tank layer $m_{Sto(l)}$, are all different in the FlexHeat tank and are thus

corrected. Also, the coefficient for heat loss, k_{Sto}, and coefficient for transfer between the layer, κ, might differ. These have been found experimentally in the 3-days testing of a charged tank being left alone – i.e. no system interactions.

The average heat transfer coefficient

The tests were conducted in February at an average outdoor temperature of 3 °C. An overview of the tank and which temperatures refer to which temperature sensors are shown in Figure 5, and the development of these temperatures throughout the period is shown in Figure 6.

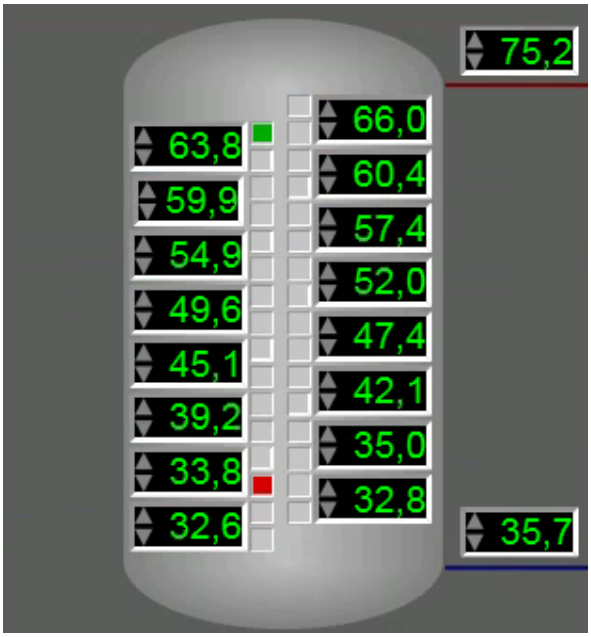


Figure 5: Temperatures in the tank. Left 1 refers to the temperature in top of the left-hand corner and right 1 refers to the temperature in the right-hand top corner. Here, these goes down the tank until 8.

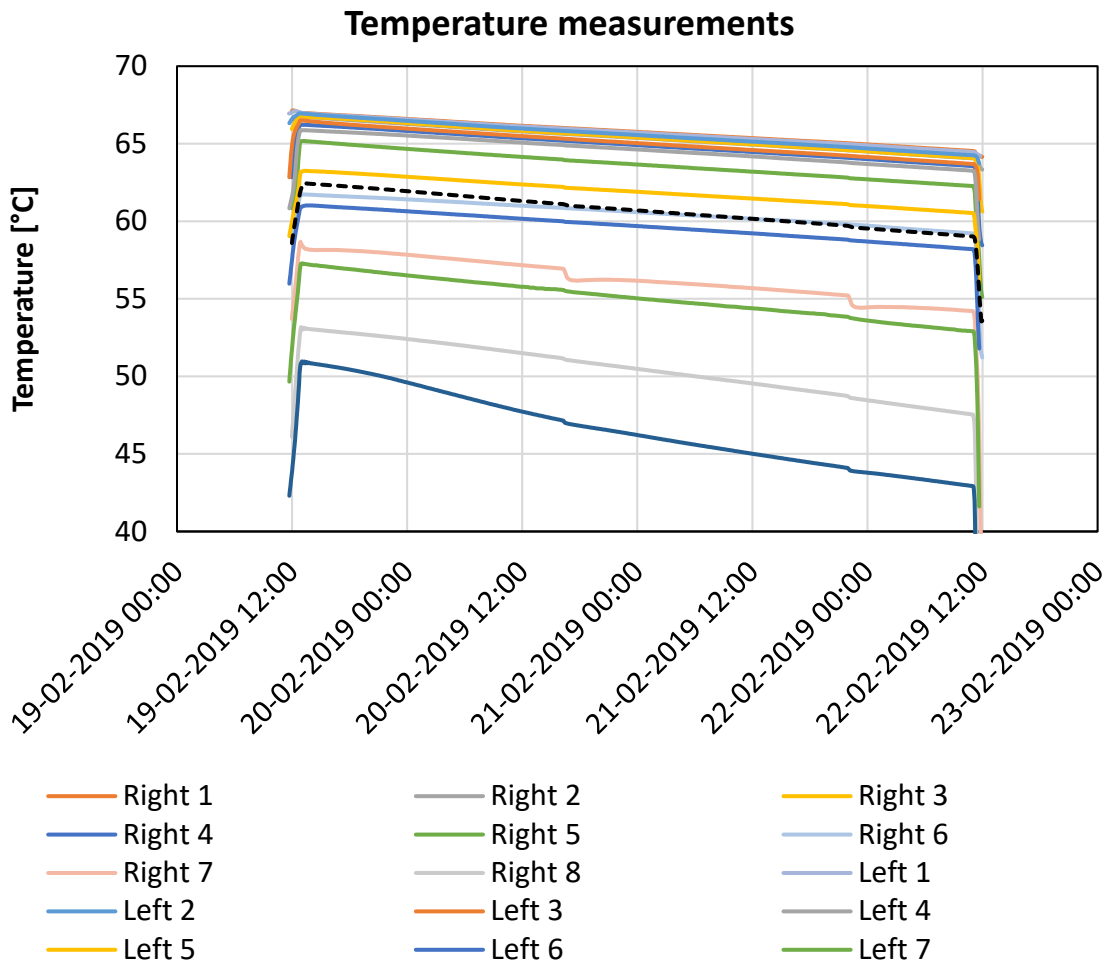


Figure 6: Development of the temperatures in the tank throughout the test period. Wiebke Meesenburg, DTU Mechanical Engineering, makes the graph.

The heat transfer coefficient may be determined for every layer individually, however this was not deemed practical. Instead an average heat transfer coefficient for the whole tank was calculated based on the measured heat loss. This average heat transfer coefficient was determined to be $1.50\ W/(m^2\ K)$. To validate this value it was compared to the one used in [1], which is only slightly lower than the value found here despite different geometries. The heat transfer coefficient is further dependent on outdoor conditions, such as temperature, wind speed and precipitation. This dependency was disregarded and the average value calculated from the test data was used in all cases for the optimization model.

The coefficient for heat transfer between the layers

To assess the heat transfer between the layers, the following layers have been defined as seen in Figure 7.

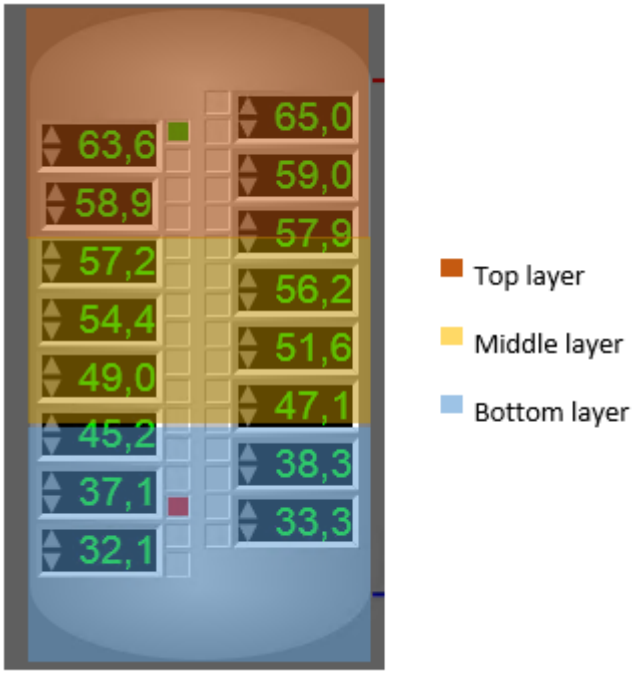


Figure 7: Stratification of the real-life tank for use in testing.

The formula showcased in [1] is utilized to calculate a new FlexHeat-specific κ.

$$m_{Sto}(l) \cdot c_W \cdot \frac{T_{Sto}(t,l) - T_{Sto}(t-1,l)}{\Delta t} = c_W \cdot \dot{m}_{Hou}(t) \cdot [T_{Sto}(t,l+1) - T_{Sto}(t,l)] - k_{Sto} \cdot A_{Sto}(l) \cdot [T_{Sto}(t,l) - T_{Env}] + \kappa \cdot A_{CS} \cdot \left[\frac{T_{Sto}(t,l-1) - T_{Sto}(t,l)}{0.5 \cdot (\Delta z(l) + \Delta z(l-1))} + \frac{T_{Sto}(t,l+1) - T_{Sto}(t,l)}{0.5 \cdot (\Delta z(l) + \Delta z(l+1))} \right]$$

The middle layer was used to calculate the conductivity parameter, as it interacts with the upper and lower control volumes. κ can be isolated given the test results. The value is found to be 93,5 W/(m K). This value is significantly higher than the values found in [1], which is in line with the large thermocline that was observed, i.e. poor stratification in the lower half of the tank.

3. Simulation results

3.1 Overview of results

The simulation results in terms of yearly heat production, the associated operation cost and the resulting heat cost are summarized in the following tables. A more detailed discussion of these results may be found in Deliverable 5.5b. The overview given here comprises the results for demand driven on-off operation (manual operation), electricity price optimization and ancillary service (FCR-N) participation. All operation modes rely on the thermal storage tank to decouple production and demand.

1. Manual operation		
Heat production	1.925	MWh/year
Total costs	542.163	DKK/year
Heat price	282	DKK/MWh

2. Optimized operation		
Heat production	1.925	MWh/year
Total costs	509.507	DKK/year
Heat price	265	DKK/MWh

3. Ancillary services		
Heat production	1.925	MWh/year
Total costs	473.294	DKK/year
Heat price	246	DKK/MWh

Table 2: Simulation results for the costs of different storage tank management strategies.

Table 2 were all conducted for 2018 electricity prices and demands using model a. The key figures here are that:

- Potential from 1 → 2: 6,03 % reduction in specific heat cost compared to case 1
- Potential from 1 → 3: 12,77 % reduction in specific heat cost compared to case 1

3.2 Optimization patterns:

A more elaborate breakdown of the consumption patterns and storage management can be seen below for two representative weeks – shown for the winter in Figures 9 and 10 and the summer in Figures 11 and 12.

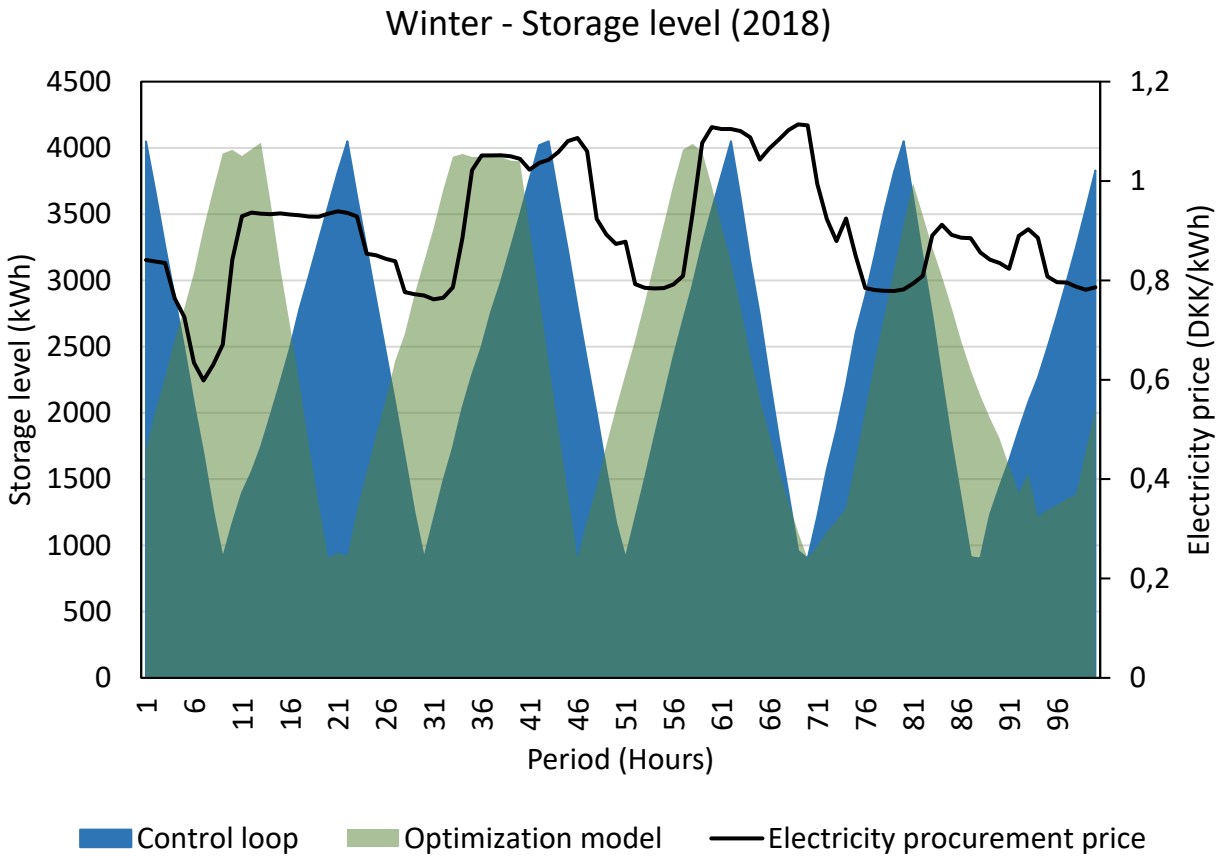


Figure 8: Storage management in the winter for the manual operation (control loop) and the optimization model. Here, the electricity procurement price is shown to evaluate when a price signal is utilized.

In Figure 8, storage management is shown. The black line denotes the electricity procurement price, which is used as a price signal to optimize the production schedule. The blue area is the storage level when implementing the simple control loop (manual operation) strategy. This can be seen by its periodic pattern of charge- and discharge as it follows the demand. The green area is the storage level for the optimization model – this one varies as the model plans the production for the heat pump more carefully and thus tries to reach the lowest costs possible.

The charge and discharge can be seen by the slopes of the storage, and it can be seen that the optimization model utilizes more of the low electricity prices as the control loop has a periodic charge- and discharge profile as it is demand-based – this is seen when the slopes are steeper at lower prices. The optimization model thus deviates from the control loop strategy indicating that a more optimal production pattern can be obtained.

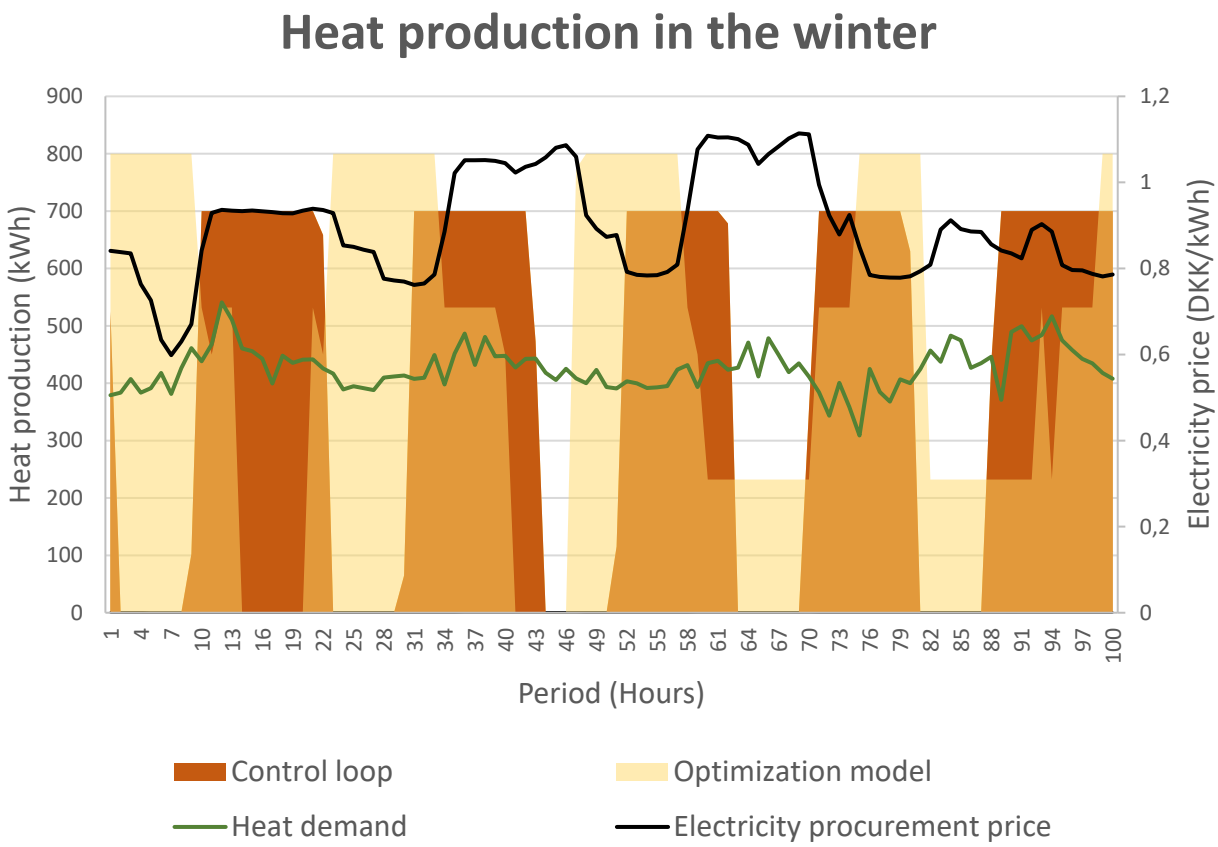


Figure 9: Heat production from the heat pump in the winter with the control loop- and optimization model strategy. Here, the electricity procurement price is an indicator for when it is more optimal to use the heat pump.

In Figure 9, the trends of Figure 8 can be examined more closely. It can be seen that the heat pump runs at full capacity in hours of low electricity price, whereas the control loop strategy runs a periodical pattern.

According to the optimization model, the heat pump runs in many hours in a row to avoid the start-up cost, but runs at minimum output level of the heat pump if the price is higher. This gives significantly less start-ups for the heat pump when using the optimization model compared to the control loop. This indicates that the optimal result might differ when changing the start-up cost of the heat pump.

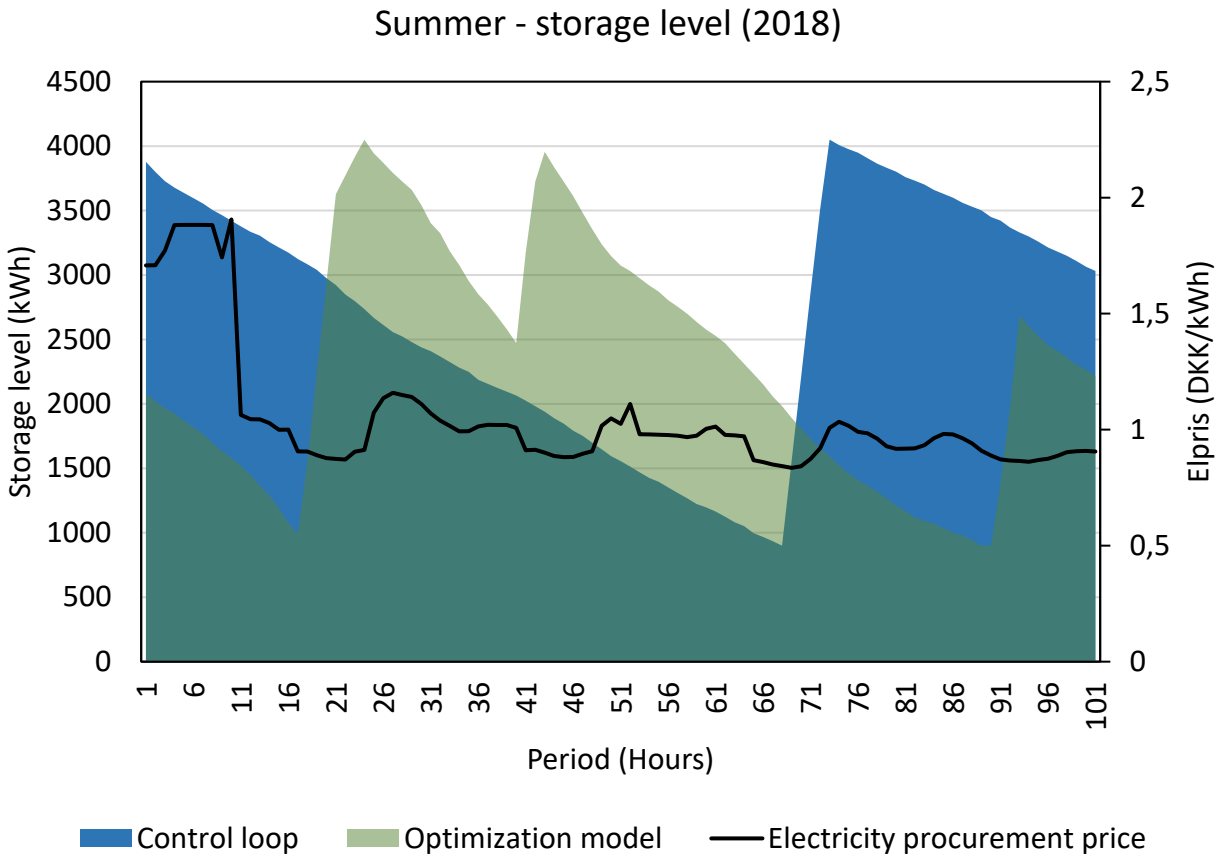


Figure 10: Storage management in the summer for the control loop- and the optimization model strategies. Here, the electricity procurement price is used as a price signal for the optimization model to utilize.

The differences in the summer are significantly larger than in the winter as seen in Figure 10 – this is due to lower demand. This results in higher flexibility with regard to charging and discharging times and thus a higher potential to utilize the lowest electricity prices. This can be seen in Figure 11.

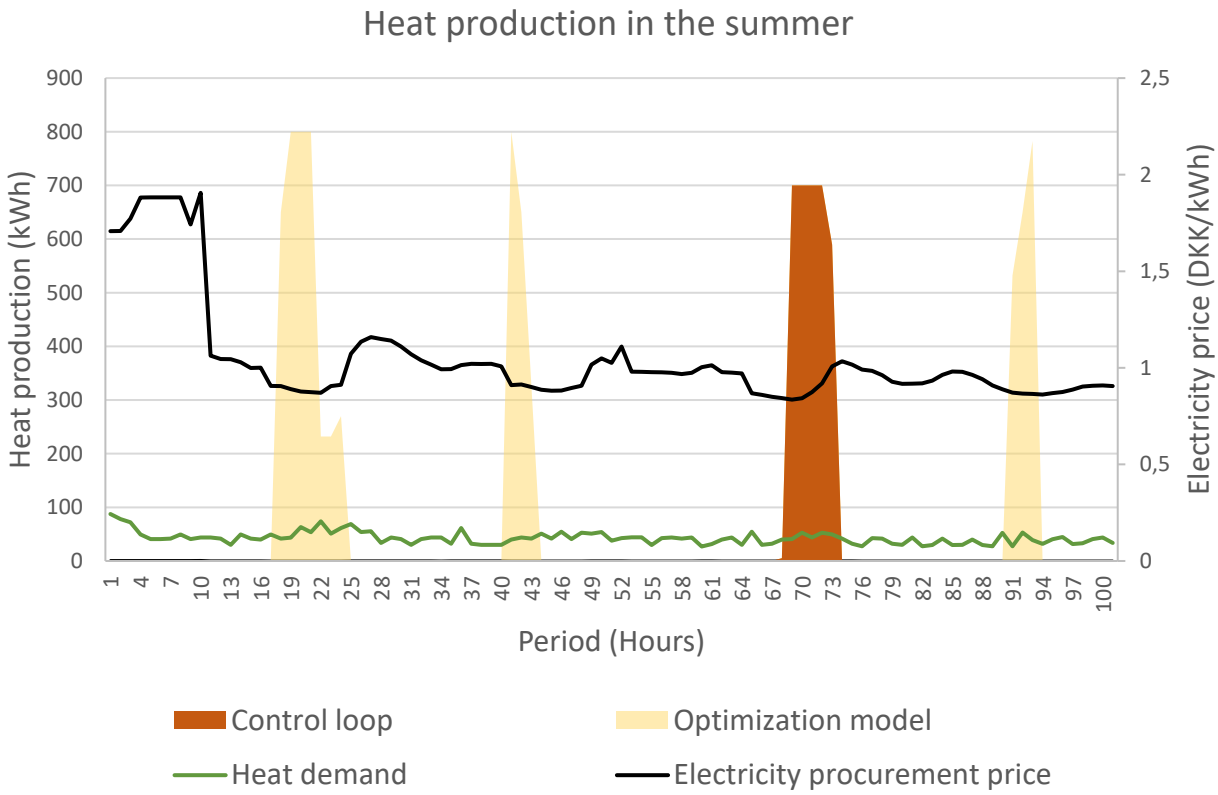


Figure 11: Heat production from the heat pump in the summer with the control loop- and optimization model strategy. Here, the electricity procurement price is an indicator for when it is more optimal to use the heat pump.

As seen in Figure 11, the demand is so low that the heat pump only needs to operate a few hours throughout the 100-hour period shown.

4. Demonstration tests

In the demonstration test, the heat pump output is measured as well as the temperature levels in the tank. There are 16 temperature sensors in the tank, which are all used to evaluate the storage level.

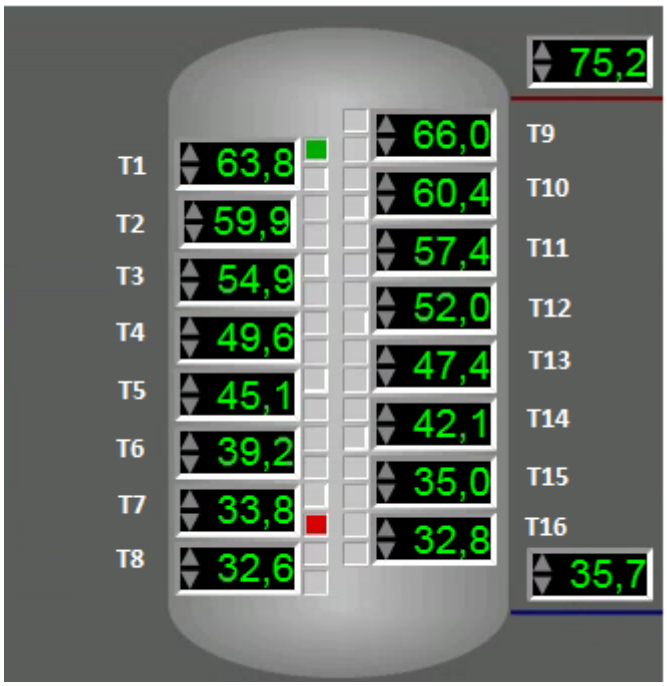


Figure 12: Snapshot of the tank to see all the temperature sensors.

In Figure 12, a snapshot of the tank is captured and the different temperature sensors are denoted for later use as these are the values, which are logged throughout the 5 days period. The temperature is used to determine the thermocline, i.e. the layer of the tank, which indicates how much useful heat is left in the tank. The thermocline moves downwards as the heat pump charges the tank, and it moves upwards as the tank is discharged. Further, the height of the thermocline may increase over time as the tank is partly charged and discharged.

The green dot is the upper-limit for the tank for when it has to stop – set at 60 °C. When the thermocline moves upwards, the temperature at this sensor will eventually fall below the set point temperature, which will stop discharging mode. The red dot is the lower-limit of the tank, which indicates how far the thermocline may move downwards while charging the storage tank.

4.1 Demonstration test

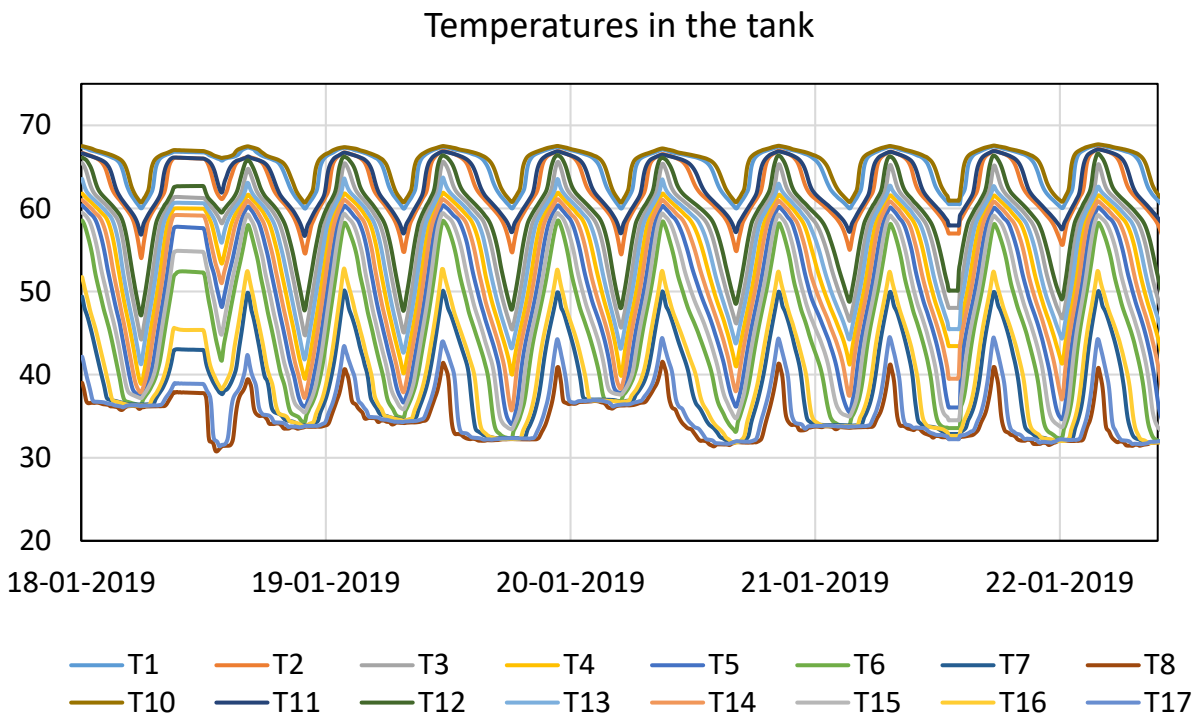


Figure 13: Temperature levels in the tank at all 16 sensors in model a).

Figure 13 shows all the temperature values in the storage tank during cycling operation (on-off). It may be seen that the temperature at the top of the tank falls during discharging. The gradient at the beginning is small and than increases rapidly before it decreases slightly again shortly before the tank is fully discharge. The maximum values stay constant during the test period as the setpoint for the supply temperature from the heat pump was kept constant. The temperature at the bottom of the tank varies. This is due to the variation of the return temperature. The spread of the temperatures between top and bottom of the tank is proportional to the energy storage capacity of the tank. Accordingly, it can be seen that the actual storage capacity of the tank varies throughout operation.

In Figure 14 The temperature distribution over the tank height is plotted for three situations – almost fully charged tank, almost fully discharged tank and an intermediate charging level. The data is taken from the same test that is represented in Figure 13, thus the temperature distribution might be influenced by the cycling operation.
It may be seen that the thermocline for the fully charge tank is more pronounced (between relative height values of 0.7 and 0.9) than for the fully discharged tank. In the latter case, no clear thermocline is visible but the temperature decreases from the top downwards with a nearly constant gradient until it reaches a minimum at 0.8. The temperature in the bottom of the tank may be higher than in the above layers in situations where the return temperature increases.

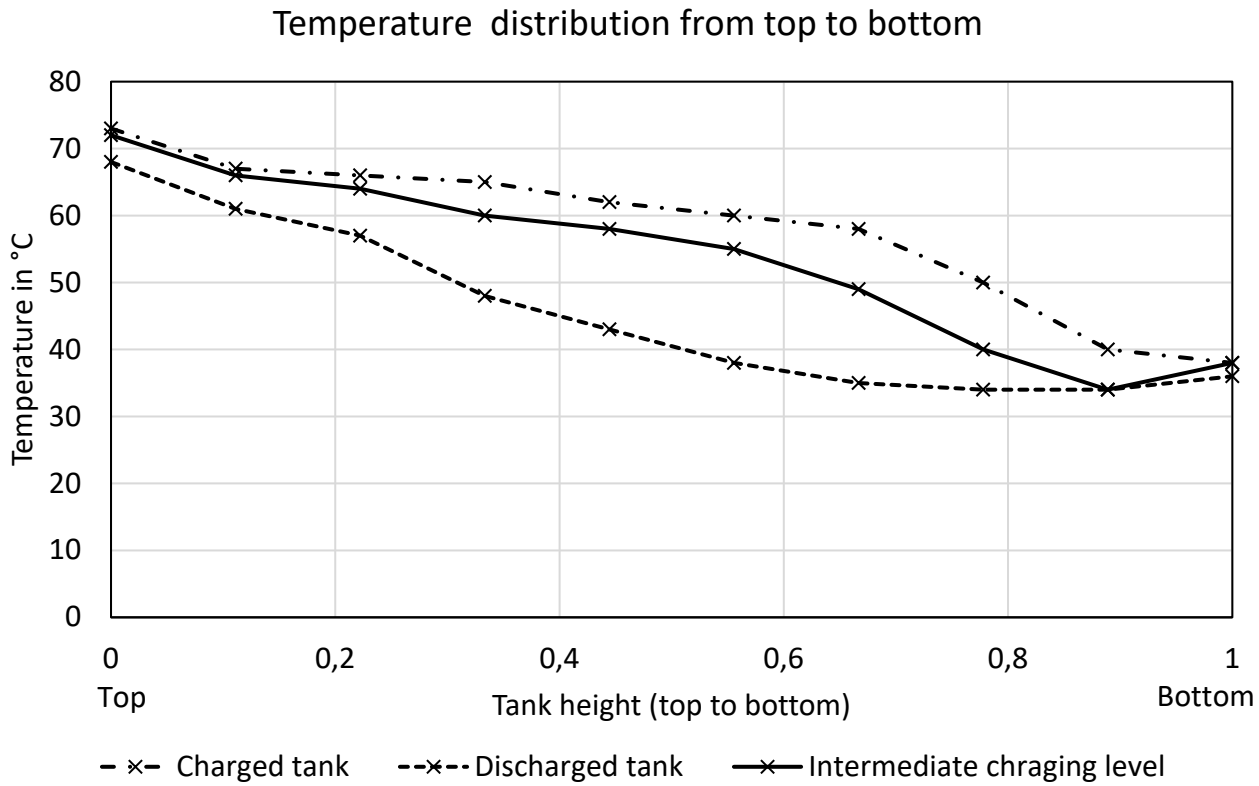


Figure 14 Temperature distribution in the tank when almost fully charged, almost fully discharged and at an intermediate charging level.

Observation over a longer period have shown that the temperature out of the tank varies between 75.38 °C to 66.95 °C with an average of 72.77 °C. The temperature at the bottom of the tank varies between 41.53 °C to 30.76 °C with an average of 34.48 °C. Using the average values, an average theoretic storage potential of 4.34 MWh may be calculated.

In the test, the storage tank is charged until it reaches 89 % of the maximum storage capacity and it is discharged down to 36 % of the storage capacity. Here, the minimum level of the tank is 1.58 MWh and a maximum level of 3.84 MWh. This correspond to a actually used storage capacity of 2.26 MWh.

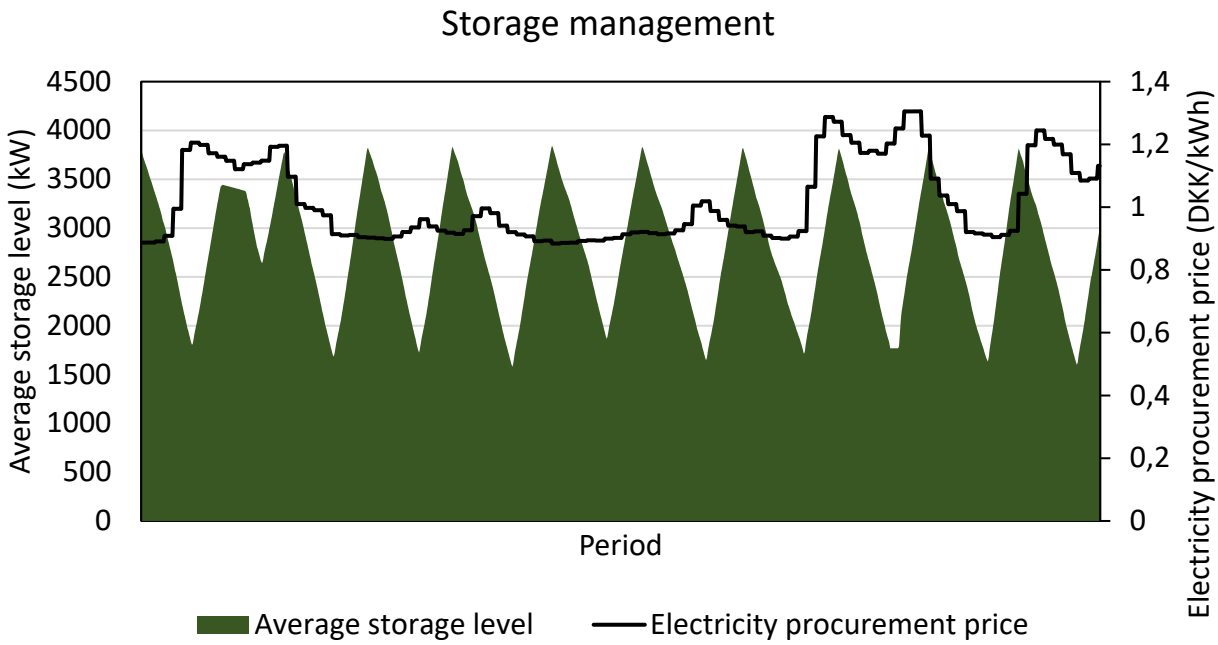


Figure 15: Average storage level over the test period calculated by the temperatures.

In Figure 15, storage management is shown with the electricity procurement price. Here, it has the same uniform charge- and discharging pattern as it is depending on the consumption where no considerations for the electricity prices have been taken. The heat production compared to the electricity procurement price can be seen in the following Figure 16.

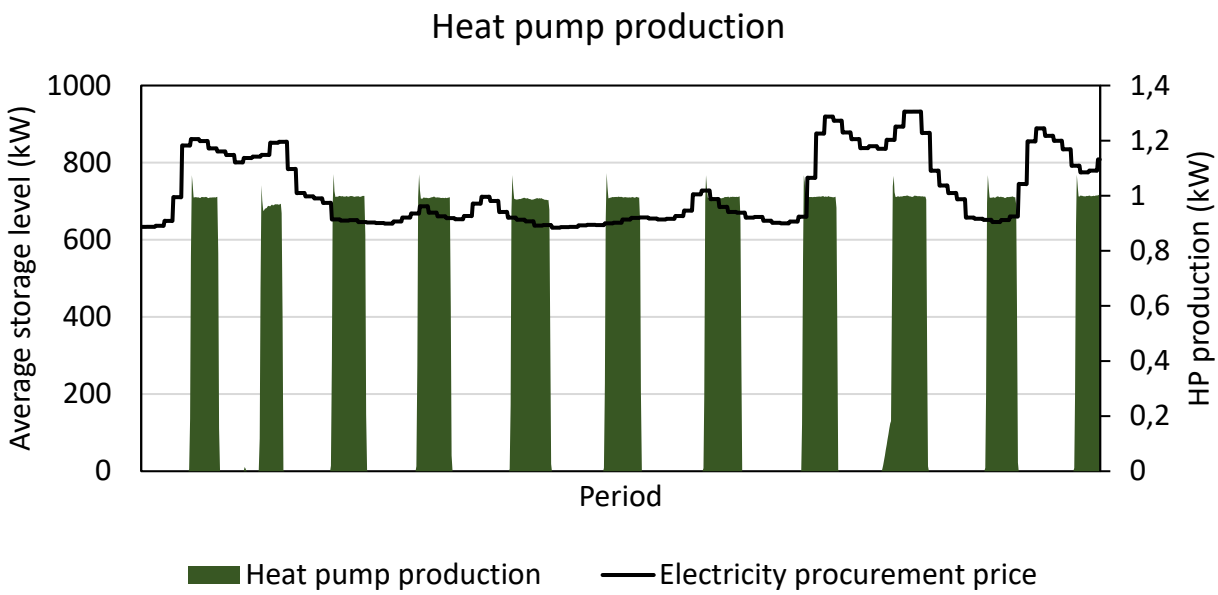


Figure 16: Heat pump production over the period.

The same horizon can be predicted with the optimization tool to see an altered schedule pattern, as shown in Figure 17.

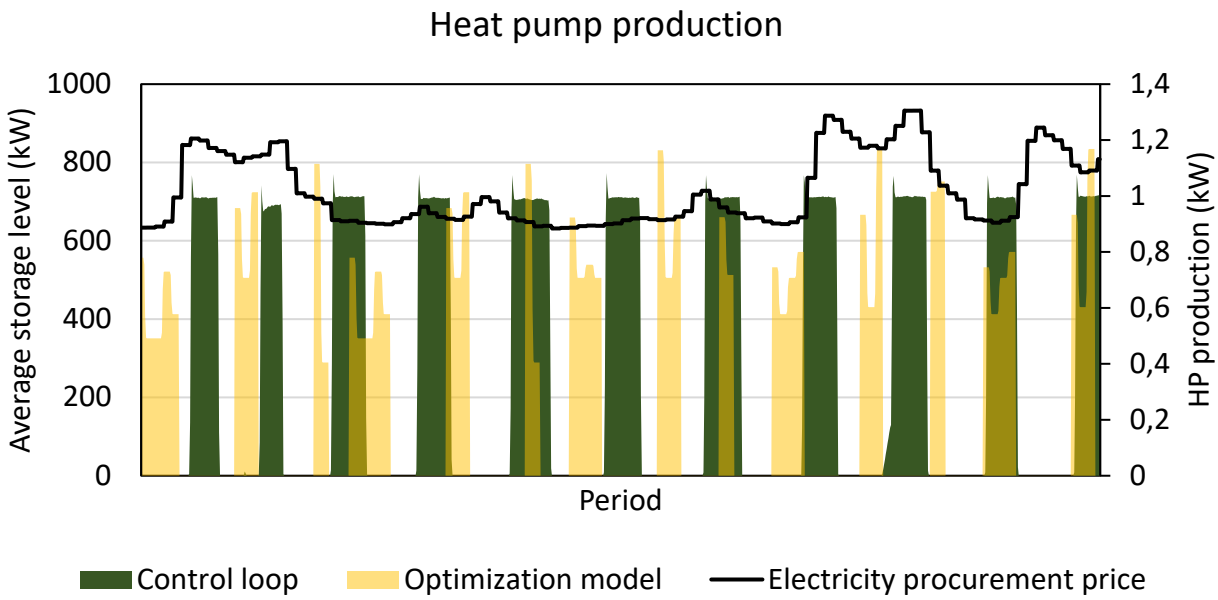


Figure 17: Heat pump pattern for the control loop as used for actual HP control compared to a predicted pattern for the optimization module.

Figure 17 is a modified version of Figure 16, where the optimization model prediction is included, too. These represent the actual values send from the intelligent module, but they were not implemented in the system. This is used for comparison to see how the system would have been instructed compared to the control system strategy. Here, the positioning is quite different as the module attempts to utilize the lowest prices. In addition, part-load is used significantly more to alternate between minimum-load and maximum load.

5. Large-scale HA in the district heating grid

The analysis performed showed how the management of a smaller HA can be utilized to optimize the system operation. This specific hot-water storage tank offers a lot of flexibility due to low consumption relative to its size.

5.1 Comparison of the FlexHeat system and the greater district heating grid

The large-scale hot-water storage tanks in the district heating grid are used a lot more for balancing production and consumption, i.e. size of the storage tanks relative to the consumption and production is lower.

The district heating of Copenhagen has two heat accumulators:

a) One at the power plants located at Amagerværket in the southeastern region of Copenhagen. This one has a capacity of 1050 MWh.

b) Another accumulator in the southwestern region of Copenhagen located at Avedøreværket. This one has a capacity of 2400 MWh.

For the following analysis, we focused on the HA located at Amagerværket (AMV). Table 2 compares the specifications of FlexHeat and AMV HA and the corresponding district heating demand.

Table 1: Overview of the HA and demand profiles. Seen for the FlexHeat island system and Copenhagen district heating.

	HA [MWh]	Total demand [MWh]	Minimum demand [MW]	Average demand [MW]	Maximum demand [MW]
FlexHeat area	4,5	1.950	0,02	0,27	0,71
Copenhagen area	3.450	4.300.000	127	634	1.500

In Table 3, it has been examined for how many hours that the HA can sustain the demand at the minimum-, average-, and maximum demand in their associated grids. This provides an indication of the relative sizes.

Table 3: Overview of the relative size between the storage tanks and their respective demand. Seen for the FlexHeat island system and Copenhagen district heating. Delivery time is defined as the storage capacity in MWh divided by the heat demand in MW.

	Delivery time at minimum demand [hr]	Delivery time at average demand [hr]	Delivery time at maximum demand [hr]
AMV HA	27	5,4	2,3
FlexHeat HA	225	16,7	6,3

FlexHeat thus provides substantially higher flexibility than the district heating grid relying on the AMV HA. Looking at the average and maximum hours, it may be estimated that AMV is required to be approximately three times bigger, i.e. 10.350 MWh to harvest the same percentage of lowered heat cost.
Here, only the size compared to the maximum demand was shown. To assess the size compared to the fluctuations in the heat demand in the FlexHeat and Copenhagen network a time dependent analysis would be needed. It may be expected that sudden variations are relatively lower in larger networks and that variations are better predictable due to the larger number of customers.

5.2 The FlexHeat flexibility applied to the district heating grid

The total heat consumption of Copenhagen in 2018 was at 4300 GWh as indicated in [2]. The heat source mix in Copenhagen is vastly different from the FlexHeat grid, as biomass CHP-production, waste incineration, peak-load gas- and oil boilers, and electric boilers are feeding into the district heating grid.

This grid mix is not taken into consideration, but a potential is assessed in Table 4 given that the storage capacity would enable the district heating system to reduce the heat production costs with the same level as FlexHeat.

Table 4: Benefits for using additional HA capacity in Copenhagen intelligently.

Potential benefits for a 10.350 MWh HA	
Heat cost saving [DKK/MWh]	17 - 36
Potential saving [10^6 DKK / year]	73,1 – 154,8

Hence, a fully equipped system with heat pumps would reap a potential benefit of around 70 - 155 Mio. DKK in annual savings. These results indicate a potential for the installment of more heat storage capacity in Copenhagen. This not directly applicable to the district heating system but merely a guideline to bring a perspective to intelligent storage usage as the following are neglected:

a) The variability in the demand from the two areas, FlexHeat and Copenhagen, are not considered.
b) Hydraulic differences are not considered – hence bottlenecks are neglected.
c) The capital cost of additional storage is not considered.
d) The capital cost of investing in a higher production capacity is not examined.
e) Differences in grid mix are not considered.

In order to accommodate c, d and e, a sensitivity analysis for investment costs and installment in the Copenhagen grid mix is issued in 5.3.

5.3 Sensitivity analysis for investment costs

The following sensitivity examines what happens if a large-scale heat pump is introduced in the Copenhagen grid mix three different scenarios:

a) A regular heat pump is introduced in the system

b) A flexible heat pump is introduced in the system
(Flexible is, in this situation, an oversized heat pump with sufficient storage capacity attached.)
c) A flexible heat pump with FCR-N capabilities
d) A flexible heat pump with limited FCR-N capabilities

Here, a) is the reference scenario in which it is evaluated on how many operating hours the heat pump will have according to the marginal heat production cost in the system of 2018, and the value of a lowered heat production cost due to the introduction of the heat pump.

In b), the heat pump has a reduced heat production cost on an hourly basis by 6,03 % based on the experience from FlexHeat. In c), the heat production cost is reduced by 12,77 % as it can deliver FCR-N as in the FlexHeat case. In d), the reduction is 9,4 % due to limited FCR-N capabilities, as larger heat pumps might not be able to provide the same relative magnitude of FCR-N to the market. This value is selected by assuming the heat pump being able to provide half the FCR-N capacity compared to FlexHeat.

The sensitivity is examined as shown in the following table 5:

Table 5: Valuation for the introduction of flexible heat pumps. The values are rounded to avoid confidentiality issues.

	a) Regular	b) Flexible	c) FCR-N	d) Limited FCR-N
Usage (hours)	2900	3200	3600	3500
Savings in marginal heat production costs (DKK/MW)	290.000	330.000	390.000	360.000
HA to HP ratio [MWh/MW]		5,6	5,6	5,6
CAPEX storage (DKK/MWh)		22.350	22.350	22.350
CAPEX HP (DKK/MW)		3.500.000	3.500.000	3.500.000
Total CAPEX (DKK/MW)		3.626.000	3.626.000	3.626.000
Increased savings due to flexibility (DKK/MW)		40.000	100.000	70.000
Over-sizing		50%	50%	50%
CAPEX (DKK/MW)		1.850.000	1.850.000	1.850.000
NPV after 30 years (DKK/MW)		- 1.110.000	- 182.000	- 41.000

The CAPEX for storage capacity can be found in [3], the CAPEX for the heat pump is reduced by 25 % compared to the values in [4]. This is an assumption made to consider

that this is for extra capacity and not the full installation of a heat pump, thus a saving can be expected in additional capacity.

The HA to HP ratio is based on FlexHeat, meaning that 1 MW of heat pump capacity requires 5,6 MWh storage capability to yield the proposed reductions in heat production costs. The green marked box in table 5 for over-sizing is the parameter of choice for examining the sensitivity in Figure 17.

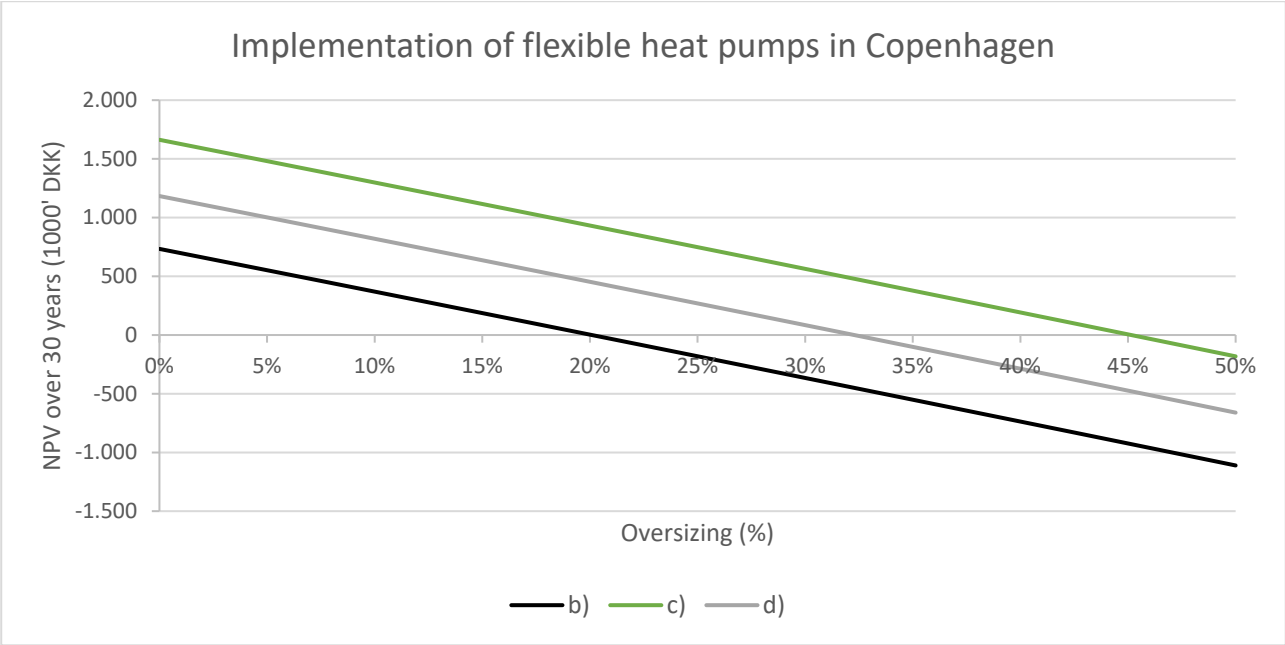


Figure 17: Sensitivity for introduction of flexible heat pumps in the Copenhagen heat market based on 2018 data. Discount rate: 4 %.

Certain considerations are important to notice regarding the sensitivity:

- The required storage is depicted here as a HA. Other flexibility sources as storage in buildings and district heating grids can be utilized as a cheaper source.
- The investment in additional heat pump capacity is not a linear relationship – hence situations can occur in which oversizing capacity can be obtained cheaper due to standard sizes from the heat pump suppliers.

If we look further into the sizing of FlexHeat, an economic optimum can be presented in Figure 18:

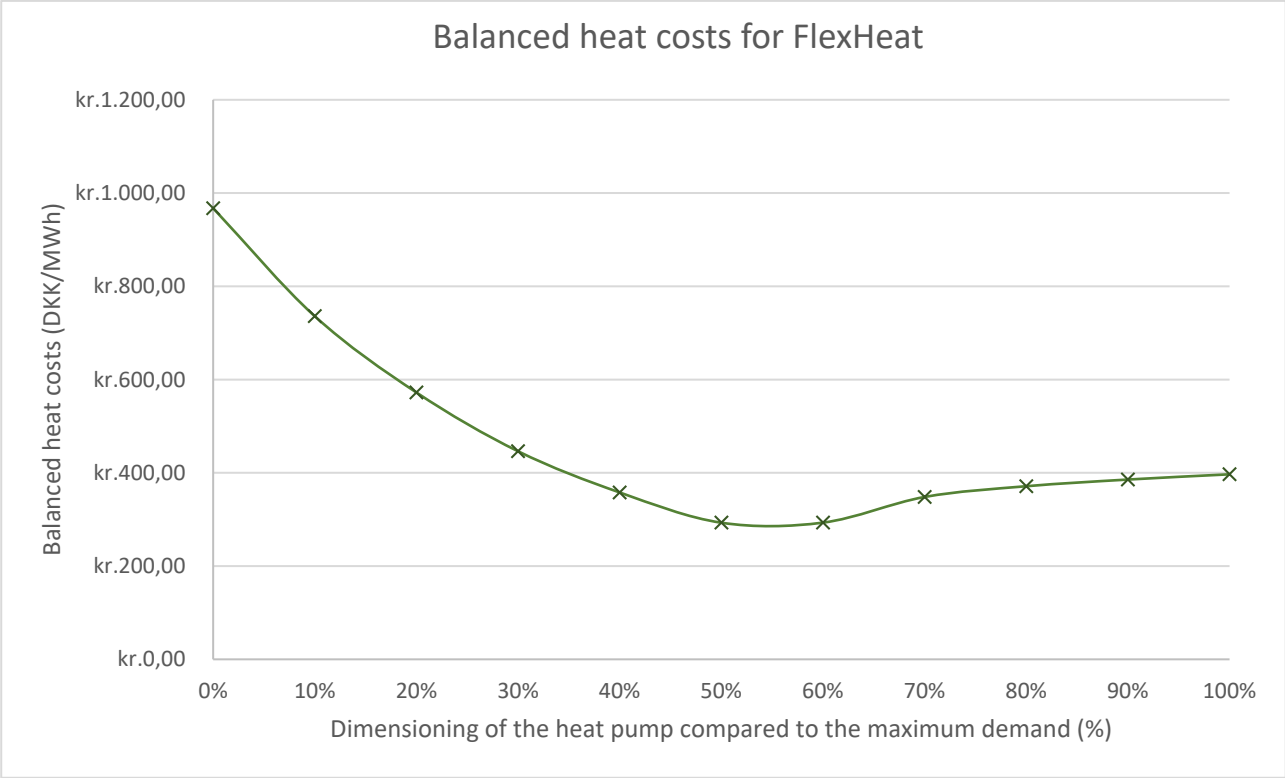


Figure 18: Dimensioning of the heat pump and electric boiler based on the balanced heat costs for 30-year period. Discount rate: 4% - balanced heat costs are calculated as the NPV of the costs throughout the 30 years compared to the NPV of the demand in the same period.

At this dimensioning, approximately 60 % capacity of the maximum load, FlexHeat would be 88 % over-sized, hence it is a non-profitable case based on Figure 17 in all of the scenarios, b), c) and d).

This case illustrates that a stronger price signal is required for district heating utilities to invest in flexible heat pumps. Some of these mechanisms are examined in 5.4.

5.4 Electricity price structure

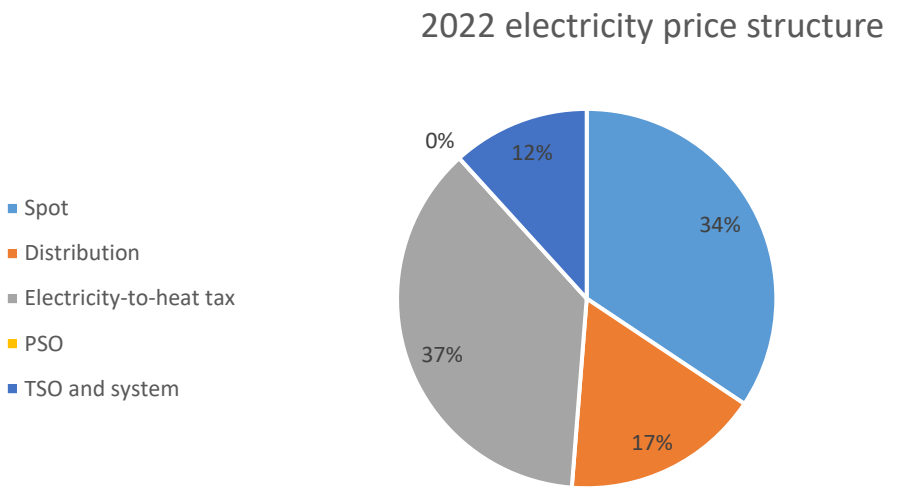
The current electricity price structure of 2019 and how it will develop until 2022 is shown in Table 6.

		2019	2022
- PSO	DKK/MWh	101	0
- TSO-tariff	DKK/MWh	38	38
- System-tariff	DKK/MWh	42	42
- Electricity-to-heat tax	DKK/MWh	257	155
- Balance-tariff	DKK/MWh	1	1
- Electricity price (2018 average reference)	DKK/MWh	239	239
- Distribution price (2018 average reference)	DKK/MWh	117	117

Table 6: Table for total electricity price in 2019 and 2022.

Here, the two parameters of interest are the PSO and the electricity-to-heat tax. The PSO is being phased out before 2022, and the electricity-to-heat tax will be substantially decreased. This means that the variable part of the electricity bill will have a larger share of the total bill, hence providing a larger incentive to schedule more intelligently. The variable parts of the bill are the electricity spot market procurement price and the distribution tariffs.

The electricity price structure is thus, at an average level, distributed in the following shares:



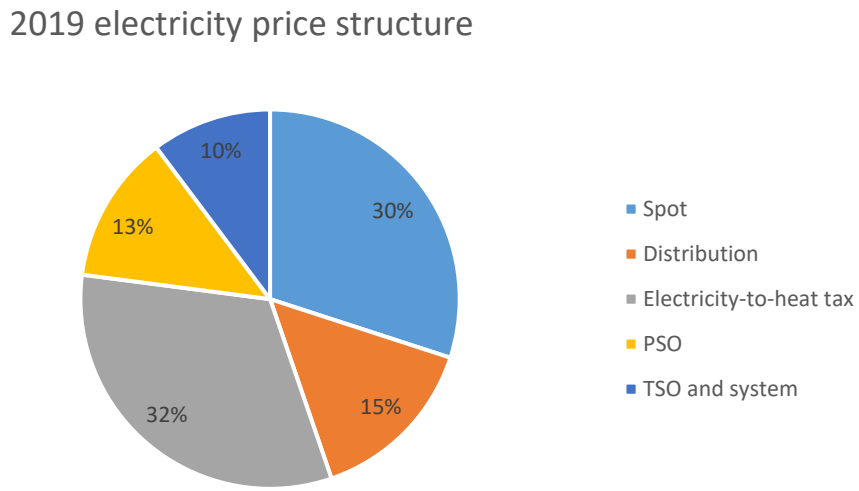


Figure 19: Breakdown of the electricity price structure based on average levels in 2019 and 2022.

In figure 19, the breakdown of the electricity price is shown in 2019 and 2022. This means, that given these assumptions, the electricity bill in 2019 consists of 45 % variable and 55

% non-variable compared to 51 % variable and 49 % non-variable in 2022. This provides an increased incentive to plan the electricity consumption more carefully in the future.

6. Conclusions and recommendations

This deliverable has shown the potential benefits of utilizing a thermal storage tank optimally in combination with electricity-driven heat production units, i.e. heat pumps and electric boilers. The tanks are utilized optimally by deploying an optimization model for the system to ensure heat produced at the lowest cost.

The model framework is verified by real-life tests on the facility, and constraints in the modelling framework are also configured given the constraint on the facility.

It was found that the heat production costs could be reduced by a total of 12,7 % if the thermal storage tank in combination with a heat pump was utilized for intelligent electricity price optimization (6 %) and ancillary service participation (6,7 %).
The FlexHeat situation compared to the district heating grid of Copenhagen concludes that an extra potential of around 70 - 155 Mio. DKK can be saved on the heat production costs if the current HA at AMV is increased three times. There is, however, a need to invest in over-sizing of the production units to harvest the flexibility, and sensitivities indicates that it is not worthwhile to invest in the increased capacity in the Copenhagen system with current price signals in the electricity system.

Outside of the scope of this analysis to consider, is the situation in 2022 in which more variable electricity prices would increase the incentive to plan the production intelligently by utilizing hot-water storage tanks. In addition, using the flexibility to provide services to the DSO is not considered either, as no services exist for this yet. FlexHeat may also be able to offer services for the local electricity distribution networks in future, which have been more thoroughly examined in WP8, UC 25.

7. Literature

[1] Thomas Schütz, Rita Streblow, Dirk Müller, "*A comparison of thermal energy storage models for building* ***energy*** *system optimization",* February, 2015,

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