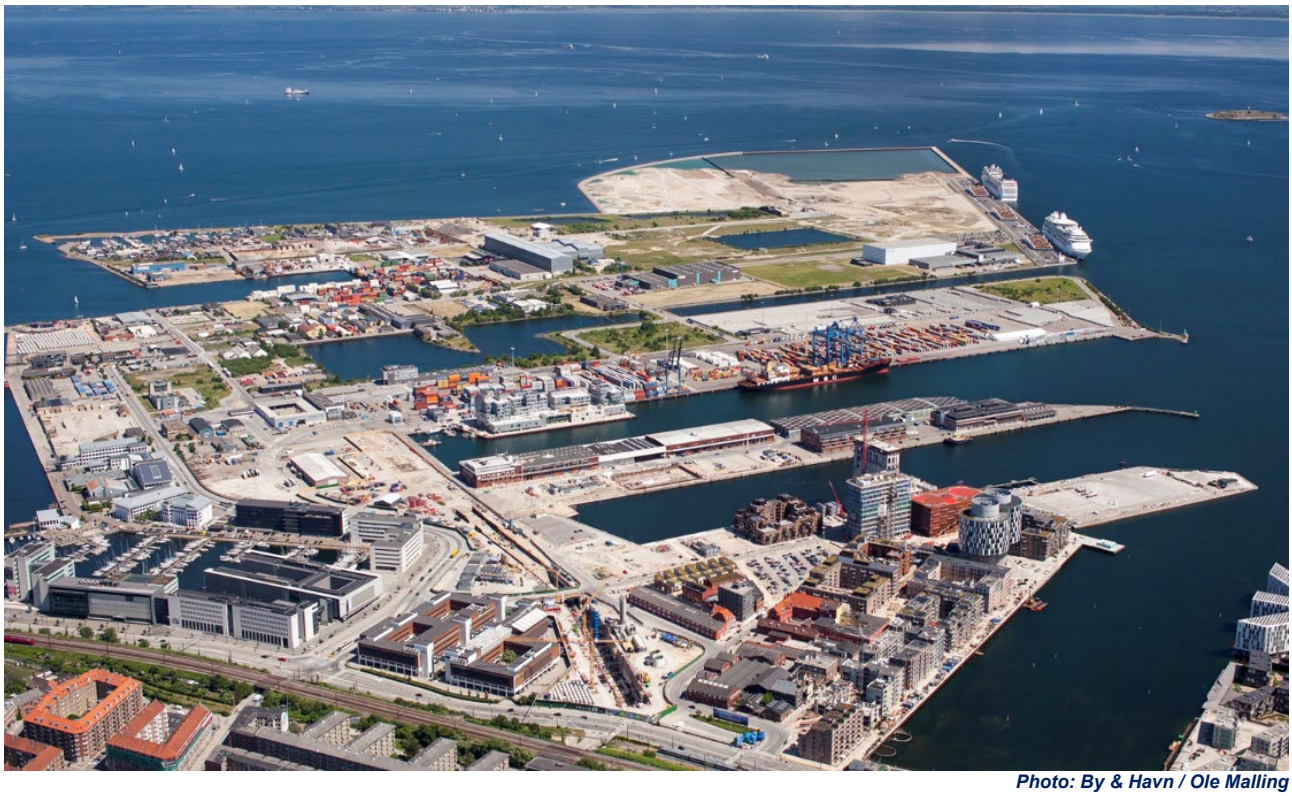
Delivery no.: 5.5b
Manual for optimized operation of an island district heating grid



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Date [26, 09, 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.

Project Information

Deliverable no.: WP5.5b
Deliverable title: Manual for optimized operation of an island district heating grid
WP title: District Heating Infrastructure
Task Leader: Tore Gad Kjeld
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Comment Period: September 26th, 2019 to October 11th, 2019

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List of Abbreviations

FCR-N: Frequency-controlled reserve – Normal
FCR-D: Frequency-controlled reserve – Disruption
aFRR: Automatic frequency regulation reserve
mFRR: Manual frequency regulation reserve
COP: Coefficient of performance
DSO: Distribution system operator
TSO: Transmission system operator

Executive Summary

In this deliverable, the concepts required for performing optimized operation of the FlexHeat island district heating grid have been examined. These concepts have been generalized in a series of recommendation, which constitutes a manual for how to operate an island district heating grid optimally.
Here, five steps for intelligent operation of the heat pump facility have been identified, in which operation becomes increasingly more intelligent and complicated; manual operation (1), optimized operation (2), DSO services (3), ancillary services (4) and combination of flexible assets (5). Here, focus is on 1, 2 and 4, as the others were examined in different projects.

For the reference case, manual operation of the system was implemented. In comparison, optimized operation of the system would yield a lower heat cost of 6 %, and additional 7 % by performing the primary ancillary service, FCR-N.

In the optimized operation case, the setup for optimizing the district heating grid has been investigated. This setup includes building blocks of demand forecast, forward temperature regression, differential pressure regression, electricity procurement price, stratified storage tank model and production planning optimization. All of these elements come together to determine the optimal schedule for the heat pump to produce for the next day.

The work on the optimized operation strategy (step 2 as described above) led to a recommendation in the generalized manual for optimizing an island district heating grid. This includes step **1) forming an intelligent optimization model** by including the building blocks of the setup, and step **2) development of a control strategy for the system** with the IT-setup deployed for the strategy. Assessment of utilizing DSO-services, ancillary services and combination of flexible assets have led to the recommendation in the manual: **3) Assess potential add-on modules.**

Throughout the development of the intelligent system, tests have been conducted to validate and optimize the system further. This experience has led to the recommendation: **4) Perform iterative tests to optimize the setup.** The results and conclusions for potential add-ons and the correlated tests lead to the final recommendation of **5) Evaluation: Add-ons to the system.**

Intelligent operation of the system has been documented, but further extensions have also been proposed to enhance the optimization, which include more intelligent handling of the demand forecast, more intelligent bidding strategies for electricity procurement, real-time data integration and other ancillary services to explore.

Version Control

Quality Assurance

Author	Reviewer	Approver
		WPL group

Version	Date	Author	Description of Changes
[Official versions only]	[yyyy-mm-dd]		
1	2019-06-18	Tore	First draft
2	2019-06-26	Kristian	Comments
3	2019-08-05	Tore	Revised comments
4	2019-09-11	Brian	Review
5	2019-09-23	Tore & Wiebke	Final revision
6	2019-09-26	Kristian	Sent for approval

Status of deliverable		
Action	**By**	**Date/Initials**
Sent for review	Tore Gad Kjeld	**Tgkj/2019-08-05**
Reviewed	Brian Elmegaard	**Be/2019-09-11**
Verified	Tore Gad Kjeld & Wiebke Meesenburg	**Tgkj+wm/2019-09-23**
Approved	WPL group	**2019-10-11**

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

As a follow-up on the deliverable 5.5a, this deliverable focuses on the tools that were developed to optimally schedule the operation of the FlexHeat system and the experimental test of the intelligent operation. As a recap, deliverable 5.5a described the smart operation of the FlexHeat system, which is shown in figure 1:

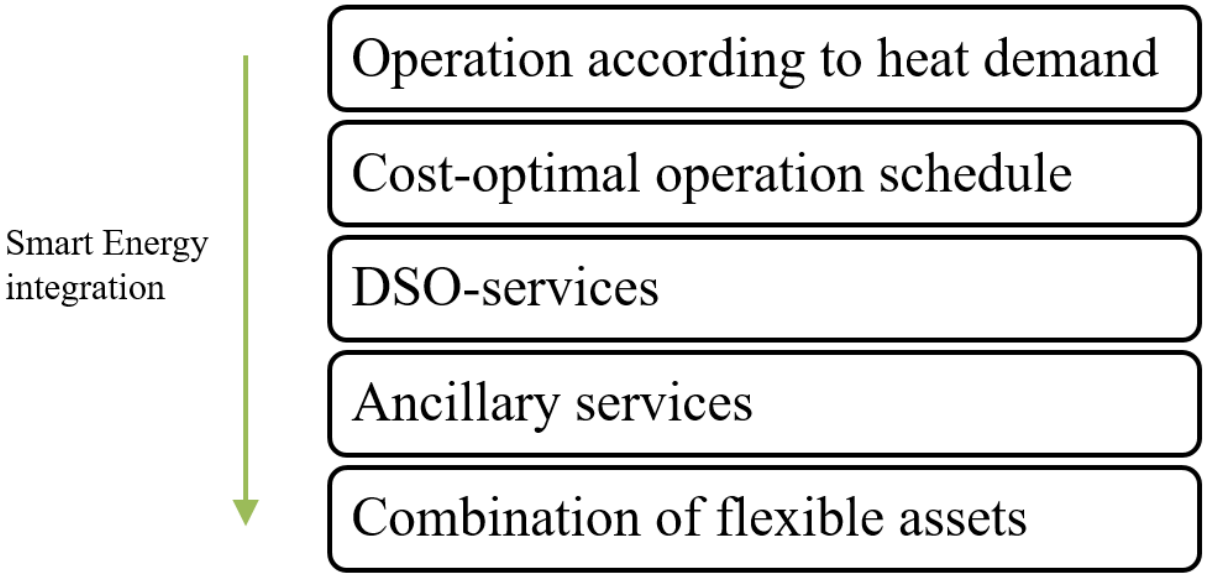


Figure 1: Integration towards the electricity sector by supplying the flexibility from the district heating sector. Source: Wiebke Meesenburg, DTU Mechanical Engineering.

Here, the heat pump is gradually used more intelligently to integrate the heat- and electricity market with the benefit of reducing the heat production cost of the heating system. These five steps summarize the Smart Energy integration:

Step 1: The heat pump is operated according to the heat demand of the consumers. The flexibility of the storage tank is only exploited to allow for start-stop operation of the heat pump.

Step 2: The flexibility of the tank is exploited to run the heat pump and electric boiler primarily when the electricity prices are the lowest, and utilizing the stored heat in the tank when the prices are higher.

Step 3: The FlexHeat system is used to help the local distribution grid by ramping the heat pump up or down depending on the conditions. If the distribution grid experiences a surplus of electricity production, which could be due to in-feed from solar- or wind power,

then FlexHeat can consume extra electricity for a period. On the other hand, if there is a shortage of electricity on the grid, FlexHeat can shut down for a period.

Step 4 here is to help the transmission grid. This is done by frequency-regulation services, which can help on a higher level of the grid.

Step 5 is a combination of other assets, for example, large-scale battery systems used for grid control or electric vehicles. A combination of the heat pump which fast regulating units, allows for a combined supply of frequency regulation services, which allows additional incomes frequency regulation that cannot be delivered by the heat pump alone.

Here, steps 1, 2 and 4 are examined thoroughly, and steps 3 and 5 are only roughly described in this deliverable. The system description of FlexHeat is not described in this deliverable as it is thoroughly described in 5.5a.

The results obtained in chapter 2-6 will afterward be summarized to a general manual on how to optimize the operation of the island heating grid.

2. Strategies

2.1 Step 1 – Operation according to heat demand

2.1.1 Strategy

Step 1 is a simplistic strategy, in which the heat pump runs at a fixed level, and heat is provided to the consumers and the leftover heat is stored in the hot-water storage tank. This is continuously performed until the storage tank reaches a sufficiently high temperature at the bottom of the tank, which indicates that no more heat can be stored. In this case, the heating system will switch to discharging the storage tank and shutting the heat pump down. This is done until the temperature level in the top of the tank is sufficiently low; indicating that there is not enough useful heat left in the tank – in this case, the heat pump is turned on and repeats its cycle.

This system can be favorable from a thermodynamic point of view as the system can be run at maximum system COP (80-88% of total capacity). The drawback is in its production planning when considering utilizing the heat flexibility towards the electricity sector – the strategy does not actively help to procure the lowest electricity prices, as it does not consider this. The strategy will randomly hit low, medium and high prices throughout the year depending on the consumers' demand, and on an average annual simulation, it will obtain average electricity prices and tariffs.

2.1.2 *Implemented tools*

No tools are implemented for this strategy other than the site-specific control of the heat pump system. The FlexHeat contractor Johnson Controls has implemented this site-specific control, based on the specifications by HOFOR and its advisor, COWI.

Here, the site-specific control is performed by setting the following:

a) Forward temperature
b) Output capacity for the heat pump
c) Boundary conditions for the storage tank

a) is set to a sufficiently high temperature in order for the heat system to deliver sufficient forward temperatures to the consumers – this is set at 75 °C in the default mode. The forward temperature cannot be set directly, but has to be set as the condensation temperature and a temperature offset, denoting the difference between forward and condensation temperature. This offset varies with operation conditions and was determined experimentally.

b) is set to 700 kW, i.e. 88 % of the heat pump capacity, resulting in a high system COP. The heat capacity can be either set directly or indirectly by giving a set-point for the evaporator outlet temperature (water side).

c) The charging and discharging of the tank is controlled according to two temperature measurements in the top and the bottom of the tank. It can be decided, both what the threshold temperatures are and which sensors to use. A sketch of this can be seen in figure 2 below:

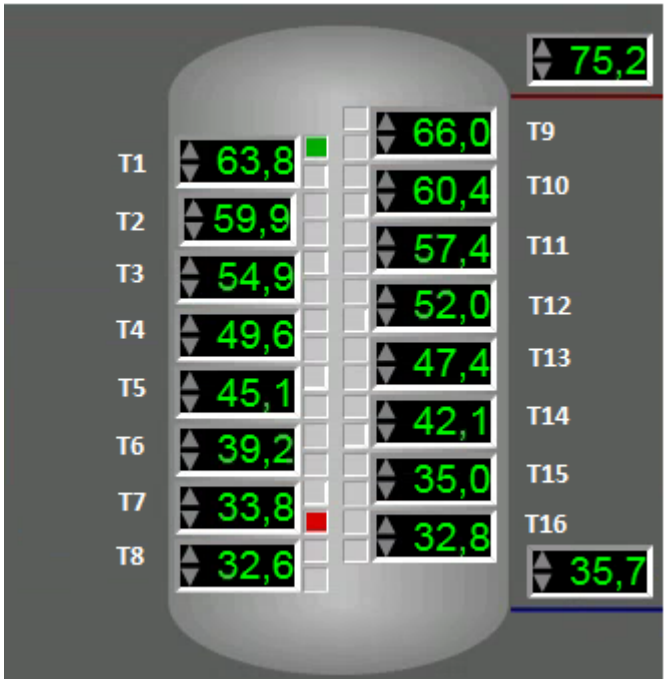


Figure 2: Picture from the FlexHeat SCADA-system with the hot-water storage tank and its boundary conditions.

Here, the green dot denotes the sensor that is used to determine when the tank is empty. This is the case, if the temperature at this sensor falls below 60 °C. Then the discharging is stopped and heat pump turns on again.

Accordingly, the red dot denotes the limit for when the tank is fully charges and the system needs to shut down the heat pump and start to utilize the tank – the threshold temperature here is set to 50 °C at temperature tracker 7.

2.1.3 Optimizing the strategy

As there are no additional tools developed for step 1, optimizing the strategy concerns tweaking the settings for a), b) and c).

In a), the aim is to reach a high enough forward temperature to fulfill any case of demand and weather conditions while keeping it at a minimum, as a lower forward temperature would result in a higher COP of the system. The 75 °C is chosen after examination of the district heating grid at different loads in the hydraulic simulation system, TERMIS. Here, the criterion is to ensure a sufficiently high forward temperature at the most critical consumer in the FlexHeat grid – terminal 3.

In b), a series of tests have been performed to investigate the system COP of FlexHeat. The results can be seen in Figure 3:

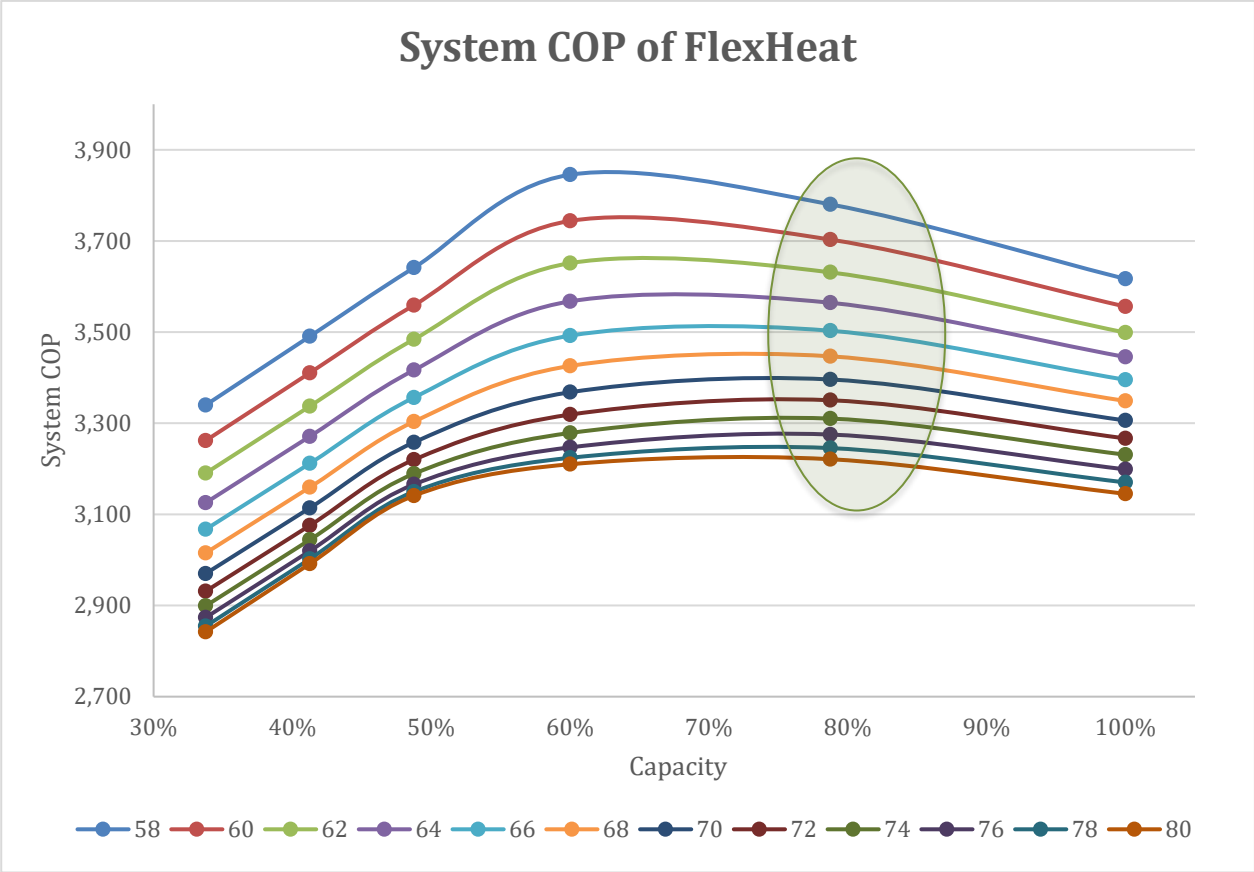


Figure 3: Tests performed on FlexHeat to investigate the system COP's.

The system COP is defined in the heat pump control system to be the following:

$$\mathrm{COP_{system}} = \frac{\dot{Q}_{\mathrm{output}}}{\mathrm{P_{lp.comp}} + \mathrm{P_{hp.comp}} + \mathrm{P_{p.pumps}} + \mathrm{P_{s.pumps}} + \mathrm{P_{g.pumps}}}$$

Hence, all the associated electricity consumption with the operation of the heat pump and the district heating system.

Here, the green-circled area is pointed out from 75 % load to 90 % as the COP is high at 70 – 80 °C and is the area in which the heat pump should operate more often than not. B) is thus selected in this area.

In c), the setting in the top of the tank is chosen to avoid a too high drop in the forward temperature out of FlexHeat. Here, the electric boilers are required to boost from the discharge temperature of the tank and the required forward temperature to the consumers – a lower set point would result in a too expensive operation due to the electric boiler boost. This setting in the bottom of the tank is chosen as if it was higher, the temperature leaving at the bottom of the tank would influence the return temperature to the heat pump resulting in a lower COP of the system – and ultimately cause a shutdown of the heat pump, as the return cannot go higher than 50 °C.

2.1.4 Simulation results

Simulating 2018 with the associated heat demand and electricity procurement costs, the following results are obtained:

Table 1: Simulation results for the manual operating strategy for system costs.

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

In table 1, the annual heat demand is supplied at a heat price of 282 DKK/MWh. This price is mainly due to electricity procurement costs but also costs related to the start-up costs for worsened COP and increased O&M. This price acts as a reference scenario for more intelligent operation strategies.

2.2 Step 2 – Cost-optimal operation schedule

2.2.1 Strategy

The strategy for this module is to utilize the thermal flexibility in the heating system to make sure that the system is operated at the lowest possible costs. The costs are primarily associated with the electricity procurement costs, i.e. electricity market price, distribution tariff, and miscellaneous electricity duties. The secondary costs are related to the marginal O&M costs for the facility – i.e. start-up costs for the heat pump, as the COP is worsened and the marginal O&M increases.

The overview of the entire intelligent strategy can be seen in figure 4.

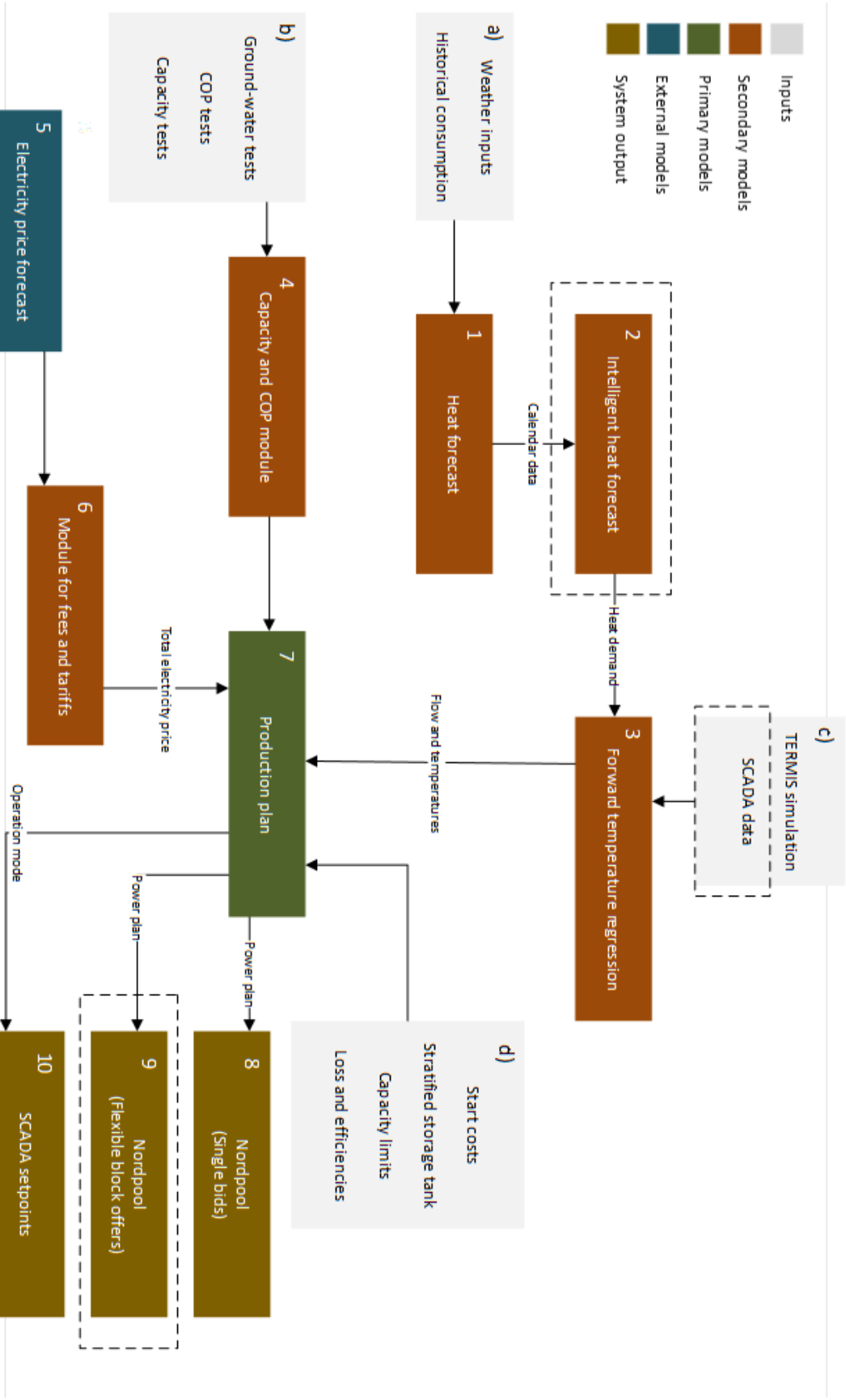
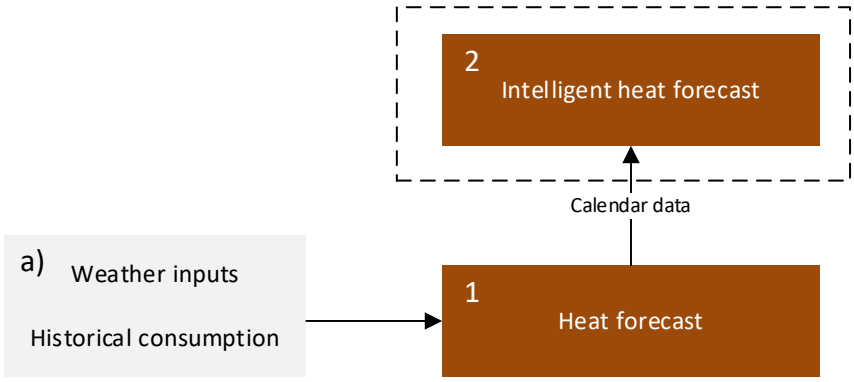


Figure 4: Overview of the intelligent control module for the FlexHeat utility

This figure presents all the required building blocks to perform a proper intelligent operation strategy for FlexHeat.

In this section, each building block will be described as well as the programs and methodologies used in the section.



In a), weather inputs are obtained from the weather forecast provider, DMI. This is historical weather data and forecast for a week ahead for temperature, wind, and solar radiation. Historical heat consumption data from the four customers of Nordhavn is obtained from the HOFOR metering database. Historic data is obtained for the year 2018 on an hourly basis, and updated a monthly to quarterly basis.

In 1, a heat forecast is performed. This is performed as a neural network, which compares historical weather data to historical consumption data to find the trends. 80 % of the data sample is used for training and 20 % is used for tests and validation of the accuracy.

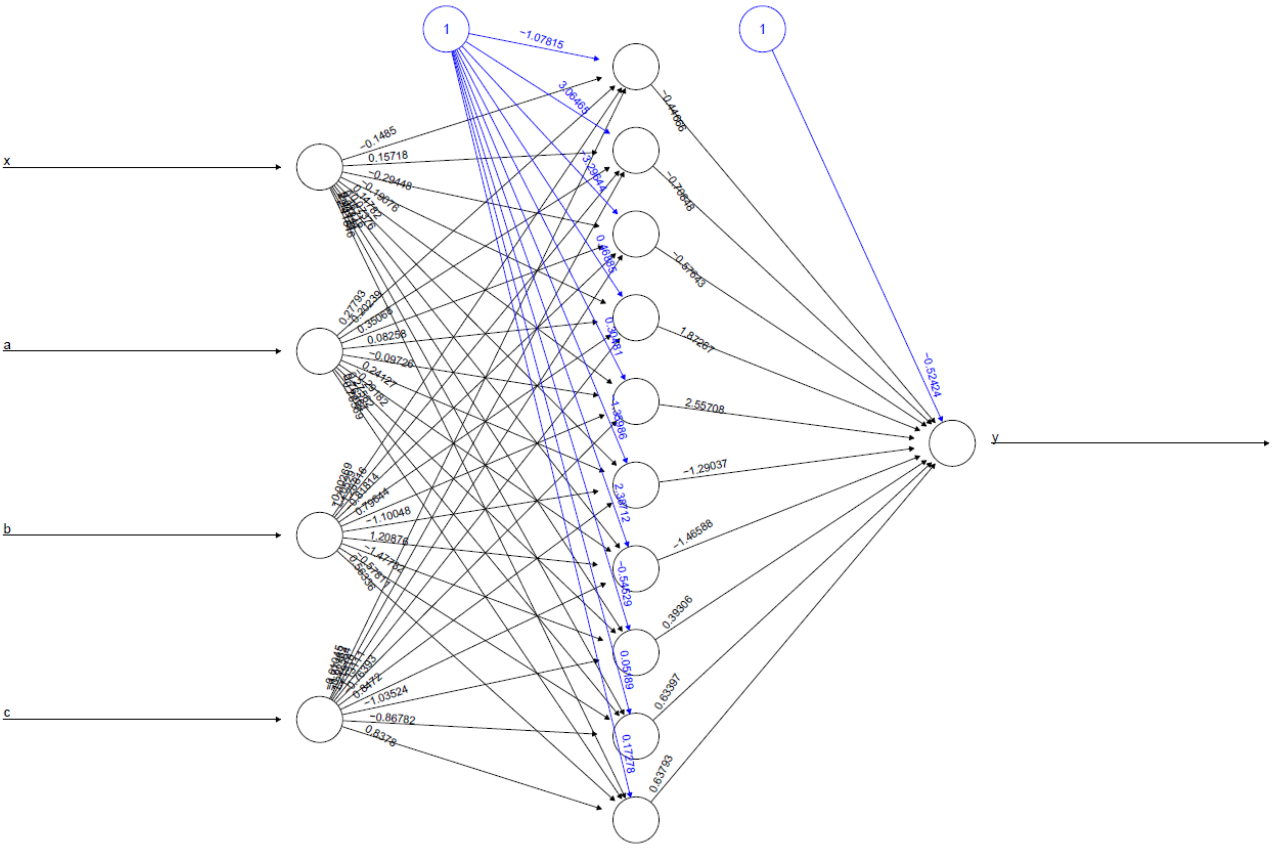
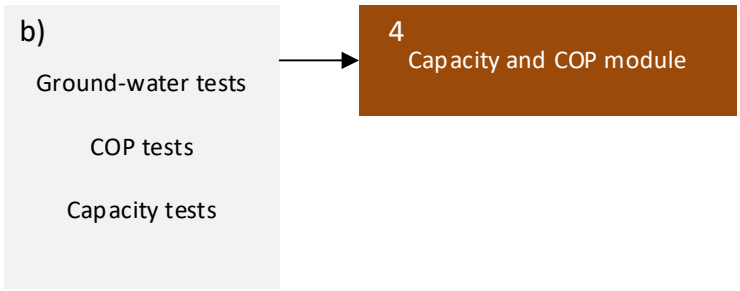


Figure 5: Picture of a trained neural network with the 3 layers: Input, hidden and output layer.

In figure 5, a trained network is presented. Here, four input neurons, which are weather data inputs, are trained by 10 neurons in the hidden layer to perform a single output – the heat demand. The weather data inputs are outside temperature, (°C), wind speed (m/s), shortwave solar radiation (kW/m^2) and longwave solar radiation (kW/m^2).

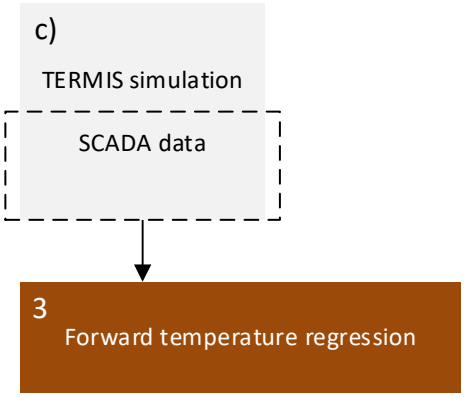
The methodology here is to train a network based on hourly and historical data, and then use this network to predict future demand on a daily basis using the weather forecast. The neural network is implemented in the program R with the neuralnet package [1].

In 2, an intelligent heat forecast is proposed in a dashed box. This denotes, that this feature is currently not implemented in the tool. It is however proposed as an extension in chapter 4.



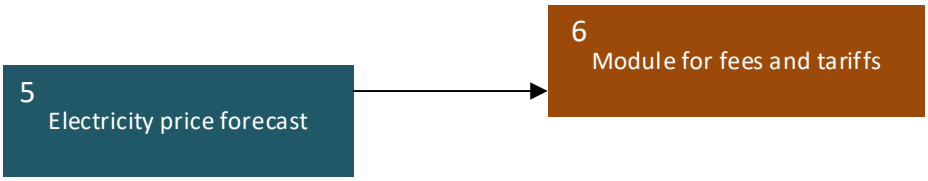
b) is a series of tests on the ground-water system, different part-load operations and different forward temperatures. Here, data for COP and capacities are logged.

In 4, the data from these tests are utilized to make a module in which any forward temperature, and capacity match a COP for the system. The graph was also presented in figure 3 in section 2.1.3.



In c), a TERMIS simulation has been performed on the grid to collect data on the district heating network-specific constraints in regards to forward temperature and pressure loss. The SCADA data, depicted in a dashed box is not implemented in the current version. It is proposed as an add-on in chapter 4.

In 3, the data from the TERMIS simulation is utilized to make a forward temperature and differential pressure regression to evaluate which forward temperature and pressure FlexHeat needs to deliver at a given demand and outside temperature to still supply heat at high enough temperatures for the most critical consumer – terminal 3. The forward temperature regression was originally performed in [2] and has been adapted by HOFOR A/S as well as adding a differential pressure regression.

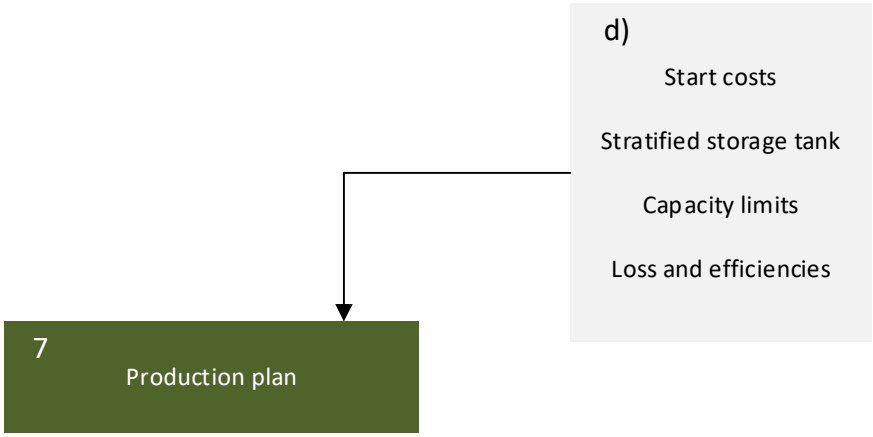


In 5, the electricity market price forecast is obtained from Markedskraft, which is a week ahead forecast with an hourly resolution for the electricity price area of Eastern Denmark, DK2.

In 6, a module for fees and tariffs are applied to the electricity market prices to obtain the full electricity procurement price of FlexHeat. The applied electricity duties in the module are the following:

- Electricity-to-heat fee
- PSO-tax
- Administration fee
- Semi-variable distribution grid fees from Radius

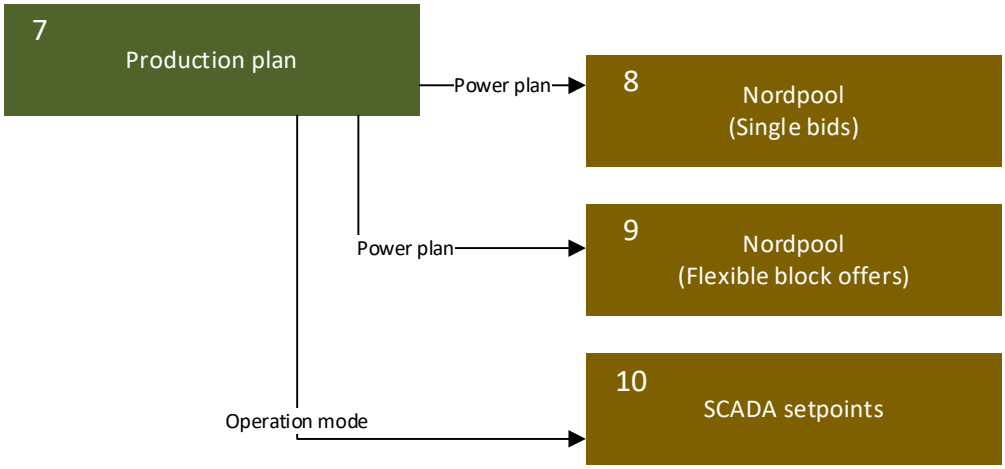
It is mostly the distribution grid fees, which requires a module as it is depended on the time of the day, day of the week, week of the year and whether it is a holiday or weekend.



In d), a series of model-specific constraints are presented. The heat pump is subject to 30 DKK per start, which is calculated based on worsened COP during start-up. The storage tank is modelled as stratified to ensure that the temperature levels are predicted accurately in the optimization model. The stratified model is based on [3].
Capacity limits and efficiencies are included for the units in the system.

In 7), all the different elements are included in a model for the production plan. This is a mixed-integer problem (MIP) optimization model with the CPLEX solver performed in

GAMS. The optimization model thus has a rolling optimization horizon, in which it schedules the heat pump production in an optimal manner. In this case, it is able to produce the needed quality of heat supply at the cheapest possible costs by utilizing the thermal flexibility in the system. The system is optimized for every 48 hours, but only 24 hours are utilized – this is to ensure that the heat storage is properly optimized for the next day.



The production plan produces several outputs. Based on the electricity consumption of the site, consumption bids are provided to the electricity exchange, Nordpool Spot, to purchase the right amount of electricity for the coming day. These are the outputs in 8. The outputs in 9 is a different strategy for purchasing electricity at Nordpool Spot, which is not utilized in the current setup – hence the brackets. This is explained more thoroughly in chapter 4.

In 10, the production plan instructs the real-life heat plant facility by producing several set points:

- Operation mode (the different modes are explained in detail in Del. 5.5a)
- Forward temperature for the heat pump
- Forward temperature for the electric boilers
- Evaporator outlet temperature set-point for the heat pump
- Differential pressure

These setpoints are sent from a calculation server to the SCADA-system, which supervises and controls the heat pump system.

2.2.2 Implemented tools

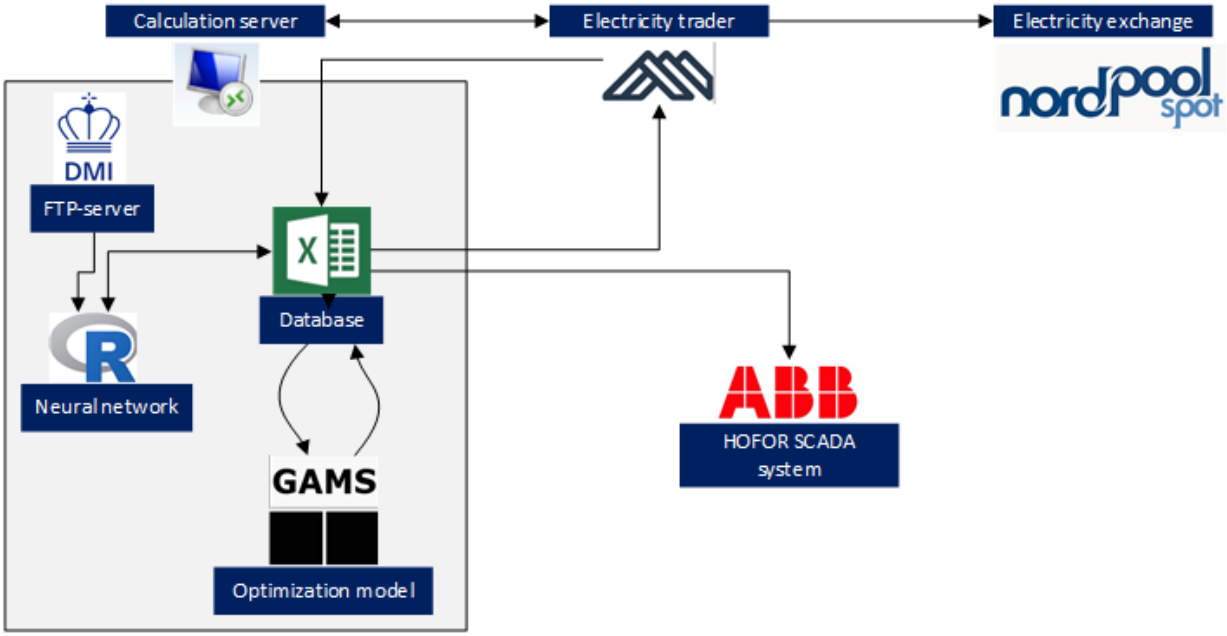


Figure 6: Overview of the implemented tools for FlexHeat intelligent operation

Figure 6 shows the data flow from the calculations server to the electricity trader and instruction of the SCADA system. The implemented tools for this strategy is in the grey box, which are features on the calculation server. This includes:

- An FTP-script to connect to DMI-server and the server of the electricity trader. This is to obtain a weather forecast and an electricity price forecast.
- Neural network in R to perform heat demand forecasts.
- A common database performed in Excel to collect data inputs, perform data analysis and produce outputs. In more details:

  - Obtain weather forecast from the DMI-server
  - Structure the forecast and produce an input for the R-model
  - Obtain the heat demand forecast from the neural network
  - Add forward temperature and differential pressure module
  - Obtain electricity price forecast
  - Add tariffs and fees
  - Collect heat demand, forward temperature, differential pressure, electricity prices as an output to the optimization model
  - Collect output from the optimization model
  - Send data to the electricity trader
  - Send set points to the SCADA system

- An optimization model performed in GAMS for the production plan.

2.2.3 *Optimizing the strategy*

The strategy has been tested and improved iteratively in which tests are conducted and changes to the model are performed, and the system is tested once again. This process has resulted to be more accurate on the following parameters:

- COP modeling
- Storage losses and temperatures
- Start-up costs

2.2.4 *Simulation results*

Simulating 2018 with the associated heat demand and electricity procurement costs, the following results are obtained:

Table 2: Simulation results for the optimized operating strategy for system costs.

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

In table 2, the annual heat demand is supplied at a heat price of 265 DKK/MWh. This is an improvement of 6 % by utilizing the price signals in the electricity market price and distribution tariff structure, compared to simple operation mode (2.1 Step 1), which was used as a base case.

2.3 Step 3

Step 3 is not investigated in this deliverable as it is examined elsewhere. The heat pump system has a central role in project DREM. DREM, DSO role in electricity markets, investigates future scenarios for anticipated issues in the local electricity grids on distribution level. There are two possible issues: a) electricity overload and b) electricity deficit.

a) A common phenomenon in Germany, as intermittent electricity sources as wind and solar panels can provide too much production at given hours for the DSO to handle. Flexible electricity consumers like a heat pump can increase their consumption at these hours to help the DSO to balance the grid.

b) As more consumers that are flexible enter the market, heat pumps, electric boilers, electric vehicles, etc., the coincidence factor for electricity consumption increases leading to electricity deficits of the grid. This can be helped by contracted flexible units, which can shut down in the peak hours for consumption to sustain the grid.

The situations are also investigated in WP8, use-case 25, which is only about electrical overload. Here, the focus is on the contractual services that the DSO can provide to the flexible units to provide up- or downregulation.

2.4 Step 4

2.4.1 Strategy

Services

In this section, it has been examined which ancillary services the heat pump can deliver into the system. The ancillary services of Energinet are divided into three categories – primary, secondary and tertiary reserves.

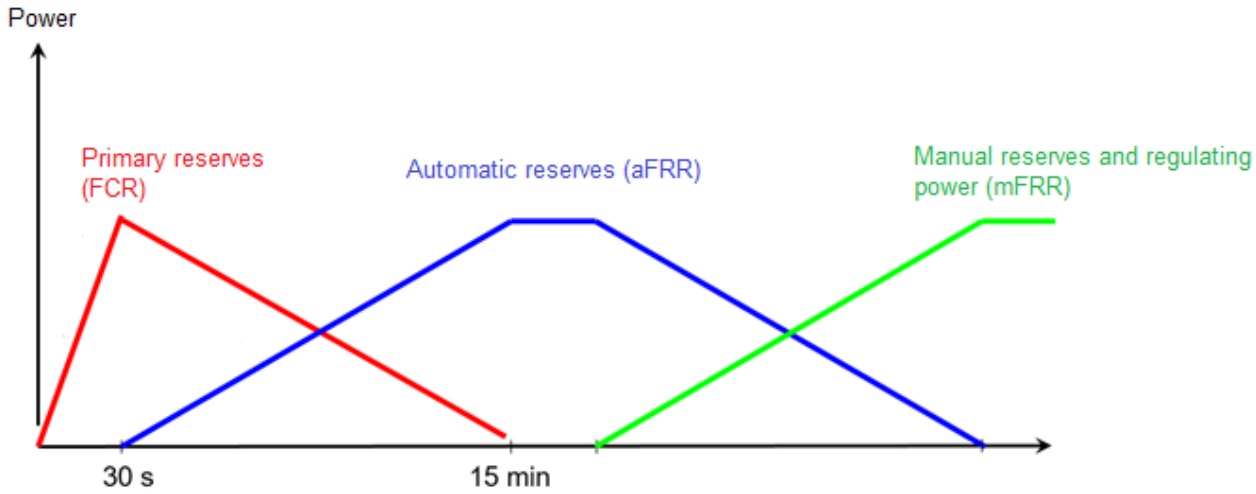


Figure 7: Types of services ordered by Energinet for ancillary services.

Figure 7 shows the types of reserves and characteristics. The primary reserves are the fastest reserves to stabilize the small deviations in the frequency, and low capacity is required. The secondary reserves are slower, 5-15 minutes, and the objective is to stabilize the frequency while recharging the primary reserves. The tertiary reserves are 15 minutes and the objective is to re-establish the frequency by recharging the secondary and primary reserves.

In eastern Denmark, DK2, the following services are available:

- **Primary reserves:**
  - FCR-D
  - FCR-N
- **Secondary reserves:**
  - aFRR
- **Tertiary reserves:**
  - mFRR

These ancillary services are purchased by the TSO, Energinet, as an availability payment and an activation payment. In figure 8, the availability payment is shown for the year 2018 daily.

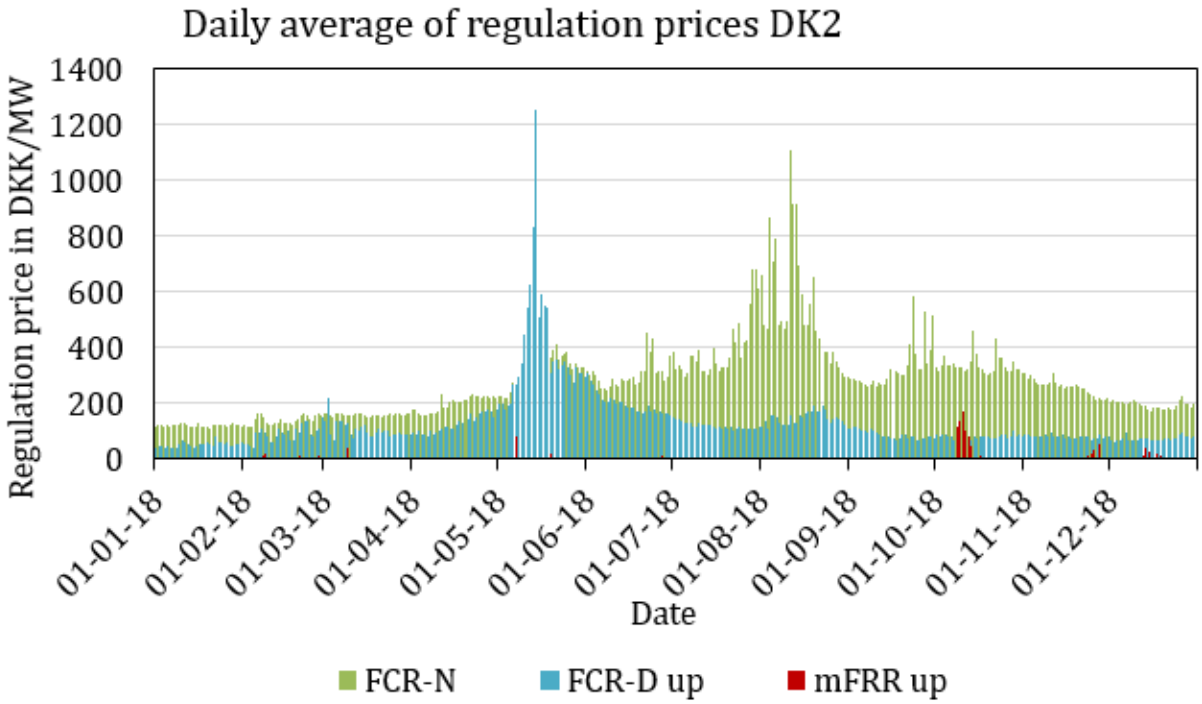


Figure 8: Availability payment for the ancillary services in DK2. Source: Wiebke Meesenburg, DTU Mechanical Engineering.

The aFRR is not shown on this figure, as the service is not available in DK2 until 2020. Here, the FCR-N service has the highest availability price throughout the year besides a short period in May, in which FCR-D is substantially better paid.

FCR-D:
The fastest reserve, which job is to regulate the frequency in the gap from 49,5 to 49,9 Hz. This has to be done within 30 seconds – first 50 % within 5 seconds and the remaining within 25 seconds. For a heat pump, this means to shut down the heat pump instantaneously. While shutting down the compressors is a relative fast process, the heat pump will require a waiting time before it can start up again, which also takes several

minutes. It is therefore deemed unfeasible to supply this very quick service continuously. A minimum regulation power capacity 0,3 MW needs to be reserved for this service.

FCR-N:
This service regulates the frequency in the gap from 49,9 to 50,1 Hz. This also means that the service needs to be delivered both ways – both up- and downregulation throughout the period. It has to be delivered within 150 seconds. This requires very fast turn on of the heat pump, or quick ramping in and out of part-load. Usual heat pump regulate too slow for this requirements. It was however deemed that it might be possible to improve the heat pump to regulate fast enough. This could be achieved by adapting the heat pump design and control, or by combination with fast regulating units. The minimum regulation power capacity bid size is 0,3 MW is needed to be reserved for this service.

aFRR:
This service needs to be delivered within 5 minutes of activation. This does not exist in DK2 until 2020, hence it is not examined in this chapter. The possibilities are described in chapter 4.

mFRR:
The manual reserve is back-up capacity, which needs to be activated for upregulation within 15 minutes. A minimum of 5 MW is needed for this service, as Energinet purchases capacity, which needs to be bid into the regulating power market that has this minimum capacity. In the future, this might decrease to 1 MW. This service is not examined further as the capacity limit is too high for the heat pump to enter the market as any terms.

2.4.2 Implemented tools

Concept
In the implemented tools, the concept of operation is examined. The most optimal service from section 2.4.1 is the FCR-N service. There is a couple of challenges regarding this, which needs to be dealt with:

- Capacity limit of 0,3 MW
- Start-stop costs
- Up- and downregulation of 150 seconds

The heat pump is rated at 0,25 MW electrical capacity. It is not ideal to shut down the heat pump during operation as it takes about half an hour to start the heat pump again. This is due to start-up time and the minimum time the heat pump has to be shut down between start-ups. Hence, the heat pump can only be regulated down to 40 % of the operation, 0,1 MW. To operate on the FCR-N market, the heat pump needs to be able to deliver both up-

and downregulation throughout the service delivery – hence, operated at 0,175 MW to provide 0,075 MW up- and down.

The electric boilers have 0,2 MW capacity. These can deliver the required downregulation for the plant, i.e. allowing the heat pump to be operated at full capacity and regulate to 40 % of the capacity – this allows for 0,15 MW. This approach seems beneficial, as upregulation requests are dominant in the FCR-N market. Hence, the concept is that the heat pump delivers the upregulation and the electric boilers deliver the downregulation.
The bid size is still too small to bid into the FCR-N market. Discussions with Energinet and the electricity trader, Markedskraft, have been ongoing throughout the project to see if the service could be delivered anyway. The discussions led to the agreement that the electricity trader could simulate an FCR-N market by using the real activation and price signals, thus allowing the system to react to frequency deviations. Another option would be to aggregate several flexible units to bid on the regulation market.
The challenge regarding start-stop costs is dealt with by only delivering this service by performing partial regulation and not a full shut down. This further allows to reduce necessary waiting times between shut-down and start-up.
The last point, the up- and downregulation times, has been examined in tests. The following testing scheme has been conducted in figure 9:

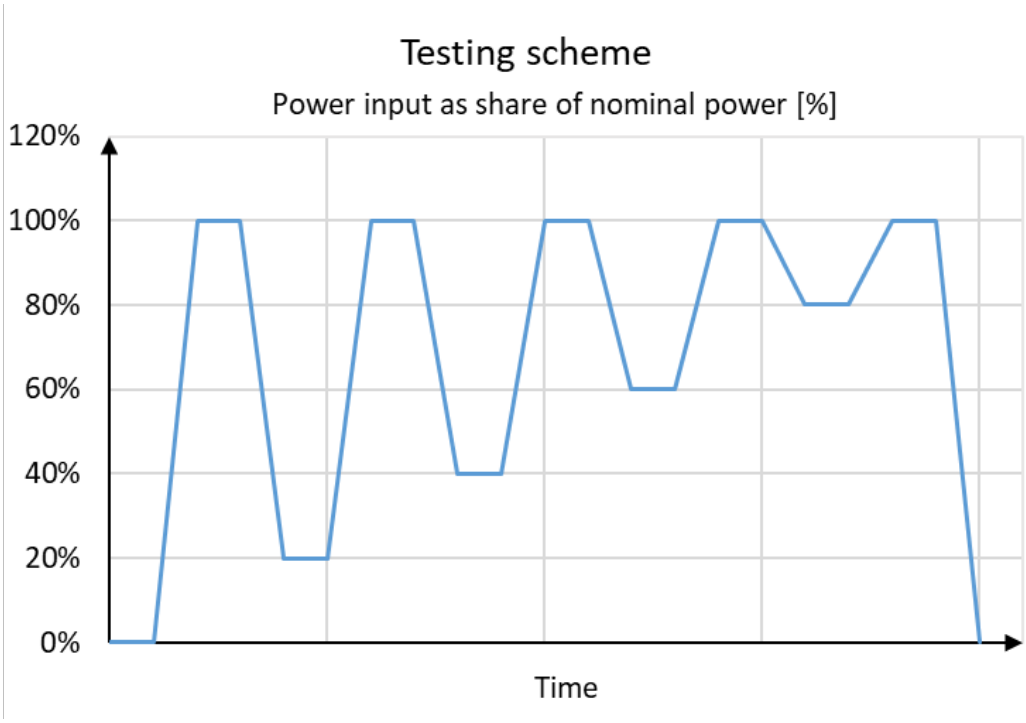


Figure 9: Test scheme for FCR-N regulation times. Source: Wiebke Meesenburg, DTU Mechanical Engineering

In this figure, the system is tested in part-loads up- and downwards from 100-40%, and the times between each regulation is recorded at forward temperatures of 60 °C, 70 °C and 80 °C.

Results can be seen in figure 10:

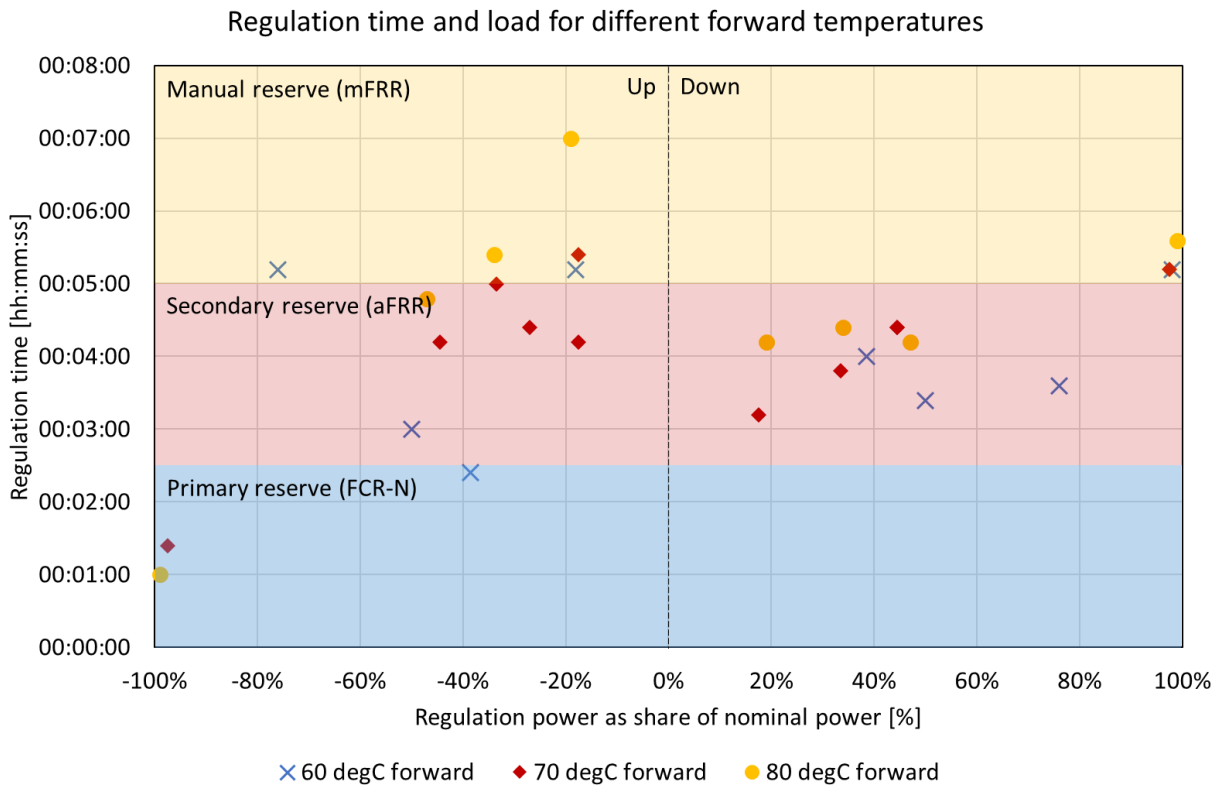


Figure 10: Up- and down regulation time for the heat pump at different forward temperatures. [4]

In the test an extensive underswing was observed after ramp down, which had the same length for all load steps. This might indicate, that a waiting time between up and down regulation is implemented in the local controller, which should be removed to allow for faster regulation. However, the cause has not been finally confirmed by the manufacturer. The results presented in Figure 10 are idealized, assuming that the underswing can be avoided or outbalanced by turning on the electric boiler. The majority of the results are in the secondary reserve region, thus the system, as it is implemented today, is too slow for the FCR-N service.

2.4.3 Optimizing the strategy

To solve the last issue with FCR-N service delivery, HOFOR A/S initiated a cooperation with the heat pump supplier, Johnson Controls, and DTU Mechanical Engineering. The aim was to examine how heat pumps could be regulated faster by identifying the limiting factors. The study indicated that one critical factor was condensation in the suction line coming from the liquid separator going to the low-pressure compressor [5].

Johnson Controls proposed different initiatives in cooperation with DTU Mechanical Engineering and COWI. Here, a certain initiative is planned on the site to see if faster regulation can be achieved. The initiative is flagged as confidential until further notice.

Further investigation of the subject of the dynamic operation of large-scale ammonia heat pumps have been described in [4]. The theoretical possibilities in regards to system configuration, which can assist to avoid condensation in the suction line at faster ramping rates have been assessed in [5]

2.4.4 Simulation results

Simulating 2018 with the associated heat demand and electricity procurement costs, the following results are obtained:

Table 3: Simulation results for the optimized operating strategy for system costs.

FCR-N operation		
Heat production	1.925	MWh/year
Total costs	473.294	DKK/year
Heat price	246	DKK/MWh

In table 3, the annual heat demand is supplied at a heat price of 246 DKK/MWh. This is an improvement of an additional 7 % by providing the most profitable ancillary services currently in DK2.

This simulation is based on the tests with the add-on to the heat pump is performed successfully, and the extra costs associated with this operation is considered in this simulation.

2.5 Step 5

Step 5 is not investigated in this deliverable as the combination of flexible assets are explored in WP8, use-case 1, in which the heat pump battery has its operation coordinated with a large-scale battery energy storage system. This use-case suggests possible scenarios in which the BESS can be used as electricity storage for the heat pump system. Another possible scenario is to combine the heat pump system with the electric vehicles, which has a charging station situated in the Nordhavn region. This has been further assessed in [6].

3. Summarizing: Manual for optimal schedule

From chapter 2, various considerations have been made to assess how to perform an intelligent operation of a heat pump system. This is a general guideline to which elements need to be considered to do so:

Manual for optimized operation of an island district heating grid

1. **Forming an intelligent optimization model**
    a. Perform a heat demand profile
        i. Procure a weather forecast
        ii. Collect consumption data
        iii. Compare these data by machine-learning methods
        iv. **Optional**: Include behavioral parameters
    b. Obtain electricity procurement prices
        i. Procure an electricity price forecast
        ii. Implement a module for adding tariffs and fees
    c. Assess your district heating network
        i. Perform hydraulic simulations on the system
        ii. Perform forward temperature regressions for the network
        iii. Perform differential pressure regressions for the network
        iv. **Optional:** Include live-data interaction with the SCADA system
    d. Implement an optimization model
        i. Develop a stratified storage model
        ii. Implement capacity limits, startup costs and COP profiles

2. **Development of a control strategy for the system**
    a. Implement the tools in 1) on a server to deliver set points to the system and electricity purchase offers to the electricity trader
    b. Complete a daily script to perform these actions

3. **Assess potential add-on modules**
    a. Investigation of local initiatives (Step 3 and 5)
    b. Investigation of system services (Step 4)

4. **Perform iterative tests to optimize the setup**
    a. Optimize the intelligent module by verifying tests (COP, losses, costs)
    b. Tests for other services

5. **Evaluation: Add-ons to the system**
    a. Add new modules to the intelligent optimization model

4. Proposed extensions

Multiple propositions for further extensions have been mentioned throughout the deliverable. These are revisited in this section to clarify the potential.

a) Intelligent heat demand module
b) SCADA data interaction
c) Flexible block offers
d) aFRR delivery

In a), the initial idea was to include the behavior of the three cruise-ship terminals. These terminals accept cruise-ships from April to September, and for the remaining period, an event company rents terminal 1 & 2 for miscellaneous activities. Therefore, the irregularities in the heat demand could be handled with a parameter indicating activity at the terminals. To do so, the consumption patterns from April to September have been studied to see if the demand increases before, at the ship's arrival and after. This is however not the case, and no change in demand could be linked to cruise-ship activity. There is, however, an increase in connection with the events during the rest of the year. 1-2 days before an event, there is an increase in demand for the terminals. It was not possible in the current setup to get accurate data for these events to include it as a module. Accurate calendar data could increase the precision of the demand forecast, as it is difficult to predict irregular behavior with machine learning techniques.

In b), a real-time module could be implemented for the system instead of relying on a predictive model to provide instructions to the system. In the current setup, traffic is only one-way towards the SCADA system. For this to be implemented properly, data from the SCADA system need to be extracted onto the server and used in the correction of the demand as well as the forward temperature optimization.

In c), the option of bidding the electricity purchase offers as "flexible block offers" is considered. The idea of flexible block offers is to choose a given time frame, say 00:00-12:00, and selecting several consecutive hours needed for electricity consumption. The heat pump might need to consume electricity for three consecutive hours at 0,25 MW per hour, here it select this in the time frame, and the algorithm by Nordpool Spot will position my consumption to provide the best social welfare – i.e. I will get the cheapest possible hour allowed by my flexible offer.
This is thus a bidding strategy in which uncertainties regarding the electricity price forecast can be limited, as the algorithm will obtain the cheapest electricity price for consumption in these hours. This is an extension to the current setup, which can be done easily from the

calculation server – there might however be some negotiations with the electricity trader to perform these offers.

In d), the secondary reserve in DK2, aFRR, is examined. In figure 11, the estimated future demand is presented:

	aFRR, DK2, behov	aFRR, DK2, indkøb
2019	-	-
2020	20 MW[14]	20 MW
2022	20 MW	20 MW

Figure 11: Forecast for future needs and purchase orders of aFRR in DK2. (Source: Energinet, 2019)

Here, it is shown that Energinet will launch this service in 2020, and as indicated in figure 7 in section 2.4.2, it could be a suitable service for heat pumps. The price signals are not yet official for the service, and the only known service is that of DK1, which has a similar service.

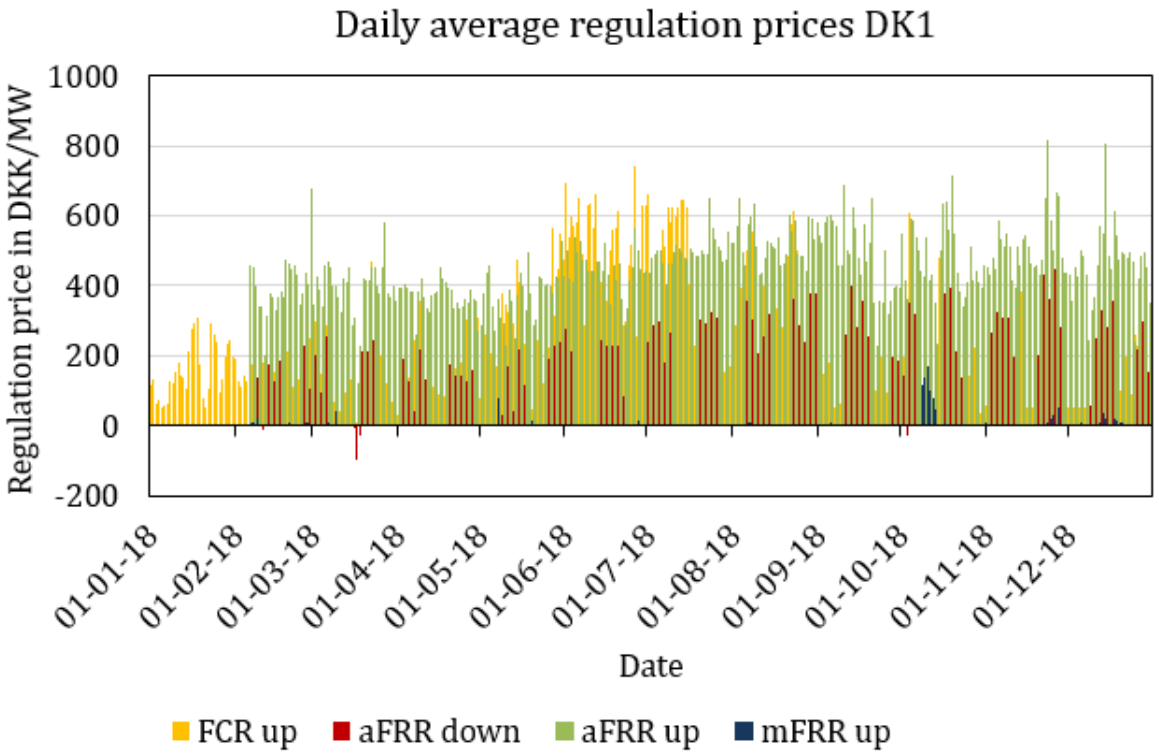


Figure 12: Prices for ancillary services in DK1.

Figure 12 shows the average prices throughout 2018 for ancillary services. Here, the aFRR is the dominant service with the upregulation being the most profitable. This would mean a downwards regulation for the heat pump which is optimal from FlexHeat point of view. Hence, more testing and concepts for delivering this service need to be assessed thoroughly for future reference.

5. Perspective

The suggested module has been implemented and applied to the heat pump, FlexHeat, in which it instructs the heat pump to operate cost-efficiently. Tests for the validity of the module have been performed in D5.3 and D8.1.1, hence this paper refers to these deliverables for further information on the tests and applicability of the module.

6. Conclusion

In this deliverable, the experiences from implementing an intelligent setup have led to a generalized manual for optimizing an island district heating grid. This manual includes the need for implementing the building blocks of the intelligent setup including heat demand forecast, electricity procurement prices, simulations on the district heating network, and an optimization model for scheduling heat production **(Option 1 in manual)**.

The optimization led to a 6 % reduction in heat costs according to simulation results for 2018. To implement this strategy on the site, an IT-setup is required, which combines a calculation server and the SCADA system with links going in and out from the electricity trader and DMI weather forecasts. **(Option 2 in manual)**.

Further extensions have been examined and suggested in the manual – specifically to look for local and regional services to be provided. In this setup, the primary reserve of DK2, FCR-N was chosen due to the technical specifications, and simulations show that an additional 7 % reduction in the heat costs can be obtained. **(Option 3 in manual)**. Tests need to be performed and an add-on to the heat pump needs to be built to deliver this service.

Hence, it is considered in the manual that iterative tests need to be performed to verify COP curves, losses, and costs in the system, but also the validity of delivering a specific service given the technical requirements. **(Option 4 in manual)**.

Eventually, it is recommended to include these new add-ons like ancillary services to the module if they are found feasible. **(Option 5 in manual)**.

These five steps are assessed to provide a framework for intelligent optimization of an island district heating grid.

7. Literature

[1] Stefan Fritsch, Frauke Guenther, Marvin N. Wright, Marc Suling, Sebastian M. Mueller, "*Package 'neuralnet'*", https://cran.r-project.org/web/packages/neuralnet/neuralnet.pdf, February 2019.

[2] Camilla Saltini, Almudena Sánchez García, "*Analysis of the Cruise Terminal island system in Nordhavn"* (Master Thesis), July 2017.

[3] Schütz, T., Streblow, R., Müller, D., *"A comparison of thermal energy storage models for building energy system optimization."* Energy Build. 93, 23–31. https://doi.org/10.1016/j.enbuild.2015.02.031. February 2015.

[4] W. Meesenburg, T.G. Kjeld, W.B. Markussen, B. Elmegaard: "Dynamic behaviour of a large-scale ammonia heat pump and the implications for delivery of ancillary services", October 2019.

[5] Meesenburg, W., Kofler, R., Ommen, T., Markussen, W.B., Elmegaard, B., 2019. Design considerations for dynamically operated large-scale ammonia heat pumps, in: 25th IIR International Congress of Refrigeration. https://doi.org/10.18462/iir.icr.2019.1203

[6] Meesenburg, W., Thingvad, A., Elmegaard B., Marinelli, M., 2019. Combined provision of primary frequency regulation using electric vehicles and a large-scale heat pump. Submitted to Energy