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Test of interrupting flexibility assets

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Abbreviations

- BRP: Balance Responsible Party
- DSO: Distribution System Operator
- TSO: Transmission System Operator
- IEC: International Electrotechnical Commission
- HP: Heat Pump
- EB: Electric Boiler
- MPC: Model Predictive Control
- BSP: Balance Service Provider
- FCR-N: Frequency Containment Reserves – Normal
- AGR: Aggregator

Executive Summary

In d7a, field tests for the DREM setup is tested on the FlexHeat facility, an island district heating system, which consists of an 800 kJ/s heat pump, 2x 100 kJ/s electric boilers and a 4,5 MWh hot-water storage tank. Here, conflict case 4, 5 and 8 was showcased from the DREM work.

In the test, open standards were utilized for real-time communication and market-based communication, IEC 61850 and IEC 62325 respectively. Furthermore, the data communication was standardized to only include 4 signals going back and forward from the flexibility flexibility asset to the BRP – this standardization would be applicable to other heat pumps as well. This was done to a secure production environment, thus proving optimal standards for cyber security considerations.

In the tests, two scenarios were investigated; a foreseen scenario, in which capacity limitations were known a day-ahead, and an unforeseen scenario, in which real-time capacity limitations were enforced. These capacity limitations were produced by a python script developed in d7b.

It was possible here to produce a local fault in the DSO grid with the script, and within 4 seconds, the flexibility flexibility asset and TSO were informed about the fault by the BRP, and within 2 minutes, the flexibility asset would be limited to fulfill the enforced capacity limitation, proving real-time data communication with the DREM system.

Beforehand, a prefeasibility study indicated that the increased heat production costs would be in the range of 150-550 DKK/MWh, whereas the field-tests indicated a range of 30-1460 DKK/MWh. Here, the foreseen results proved an intelligent way of rescheduling the heat pump to optimally handle DSO congestions – the scenarios ranged from 2 DKK/MWh to 325 DKK/MWh depending on whether it was rescheduling of the heat pump or need to start the oil boiler.

The heat pump has proven to be able to deliver DSO-services. Here, the most important recommendation is, that either of these market designs would require to deliver a foreseen signal for the heat pump to deliver optimal quality at a fair price for DSO-services. At the same time, communication to all of the actors (flexibility asset, BRP, TSO, and DSO) within the market is equally important for transparent and fair congestion management.

In the communication setup BRPs has been acting as gateway of DSO congestion management from the TPS. It proved possible to introduce both a foreseen and unforeseen scenario to a BRP system, handling automated real-time congestions of FlexHeat.

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1. Background

1.1 Introduction and scope

The DREM project have had focus on market conflicts and the role of the DSO in these cases in D2.2.
In this delivery, the focus is on the flexibility asset, and the conflicts and possibilities associated with a flexible asset on the distribution grid. The relevant cases for this specific flexibility asset are the following conflict cases:

- Case 4: TSO-DSO conflict
- Case 5: DSO counteracts
- Case 8: In-feed overload

If the flexibility asset in question were grouped with a series of other flexibility assets by an aggregator, conflict case 2, 3, 6 and 7 could be relevant. This is, however, due to the examination of a specific flexibility asset out of scope for this delivery and demonstration.
Here, the tests are limited to explore the foreseen and unforeseen scenarios described in D2.2, and seen here on Figure 1 and Figure 2:

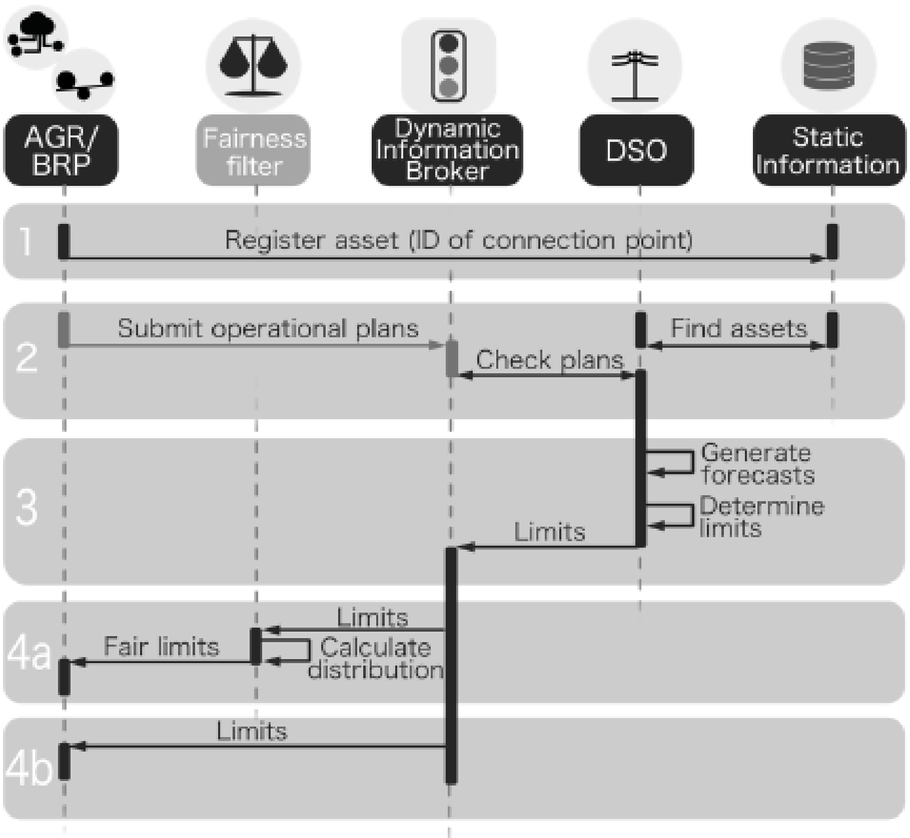


Figure 1: Message sequence diagram for the DSO to communicate a limitation in a foreseen scenario.

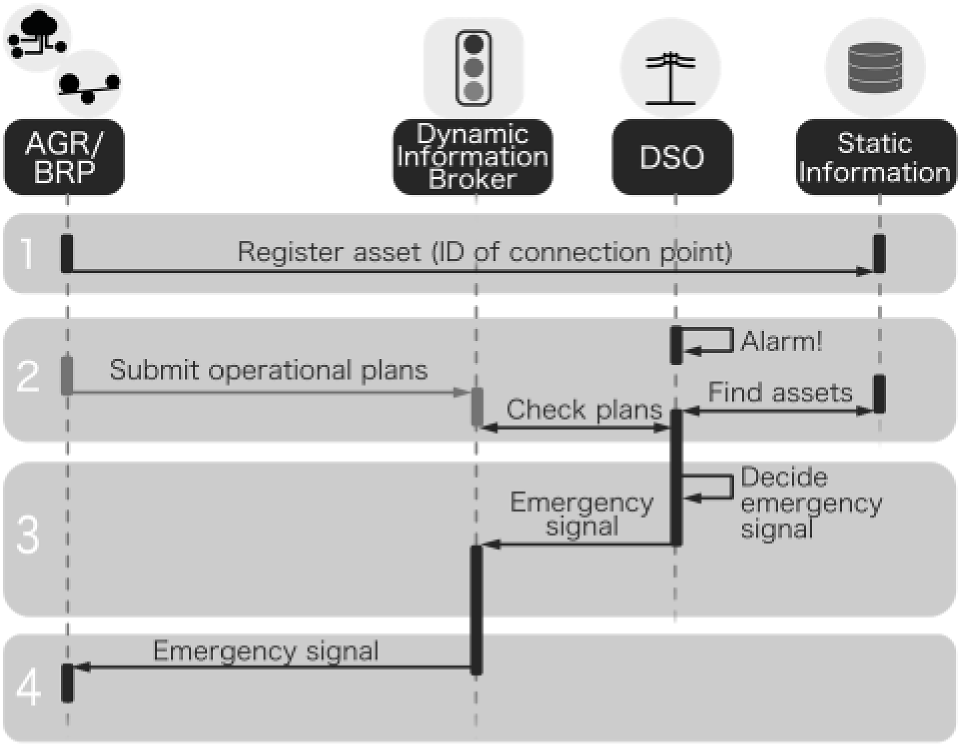


Figure 2: Message sequence diagram for the DSO to communicate an emergency signal - i.e. to perform limitations in an unforeseen scenario.

These illustrations in Figure 1 and Figure 2 set the scene in the field-test operations.

In D6.1, the suggestions for the data communication requirements have been performed. Here, market-based communication and real-time communication have the following recommendations for standards:

- **IEC 61850** for real-time data exchange
- **IEC 62325** for market-based data exchange

These standards were implemented in the field-test, and the exact setup is explained in detail in section 2.4 regarding infrastructure for data communication.

1.2 FlexHeat facility

A series of flexibility assets have been under consideration for these tests, i.e.:

- Individual heat pumps
- Large-scale heat pumps
- Large-scale district cooling chillers
- Sewage pumps
- District heating pumps

In the screening of these assets, it was concluded that the most optimal asset for field-test is a large-scale heat pump located in the outskirts of Nordhavn, referred to as FlexHeat.

Figure 3 illustrates the FlexHeat system, which is located in the outskirts of Nordhavn.

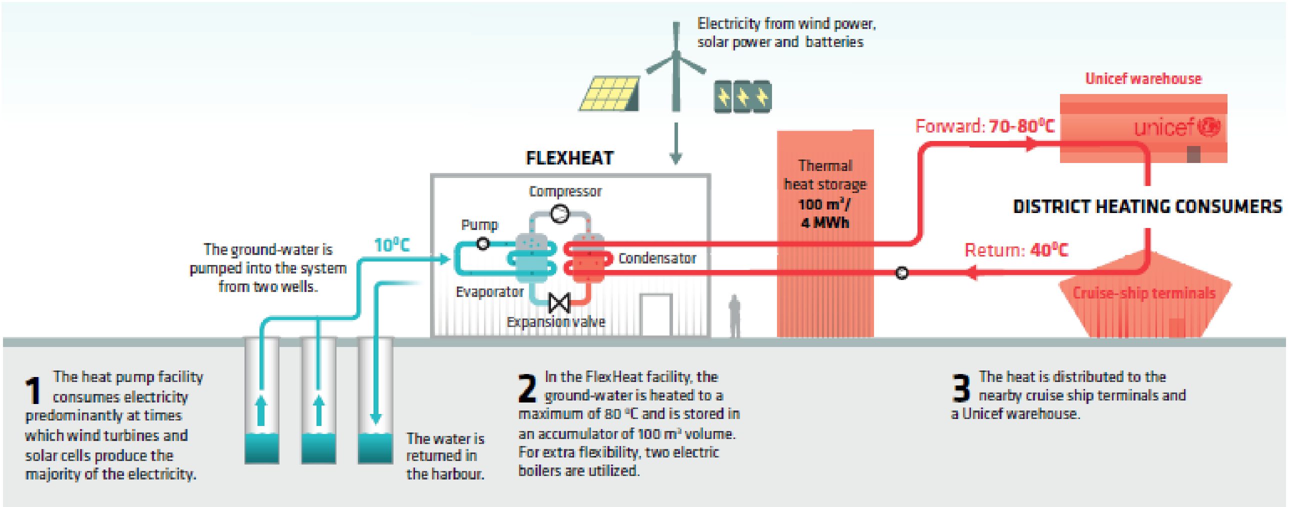


Figure 3: Illustration of the FlexHeat system in the outskirts of Nordhavn.

This location is approximately 2,7 km away from the closest connection point to the remaining district heating infrastructure, and due to a low heating demand out here, it is not yet an economically feasible case to prolong the DH infrastructure.

Instead, the four consumers in this area – three cruise-ship terminals and an UNICEF warehouse, have been supplied by two oil boilers in two separate island heating grids. These grids have been combined and supplied centrally by a heat pump system. The two oil boilers remain back-up in the area in case of faults at the FlexHeat location.

Figure 3 illustrates the principles for operation in which ground-water at 10 °C is utilized as heating source in a two-stage ammonia-based heat pump with piston-compressors, and delivers district heating in an island grid at low temperature at around 70-80 °C. This heat pump is assisted by two electric boilers and a thermal storage tank for increased flexibility. The flexibility within the island grid from the heating perspective is thus both from the storage tank, the district heating grid and the consumers. This system has 7 different modes for operation:

1- **Default operation.** The heat pump supplies the tank and the consumers.
2- **HP and EB.** The heat pump supplies the tank and the consumers. Here, the flow from the heat pump to the consumers receive a temperature boost by the electric boilers.
3- **HP Test mode**. Same as in 1, but with tweaked settings for testing purposes.
4- **Discharging.** Here, the temperature of the water at the top of the tank is sufficiently high for the storage tank to supply the consumers without any other units in operation.
5- **Discharging and EB**. The storage tank supplies the consumers, but the temperature at the top of the tank is not sufficiently high and thus will receive a temperature boost from the electric boilers.

6- **Recharge by EB.** The valves are configured in a manner to allow return water to be heated through the electric boilers and recirculated into the bottom of the tank. Meanwhile, the storage tank discharges.
7- **Fast regulation.** Here, the heat pump is controlled in an intelligent manner to deliver fast regulation to the TSO-grid, and essentially works like mode 2, but with different heat pump specifications.

A closer look at the FlexHeat facility can be seen on Figure 4.

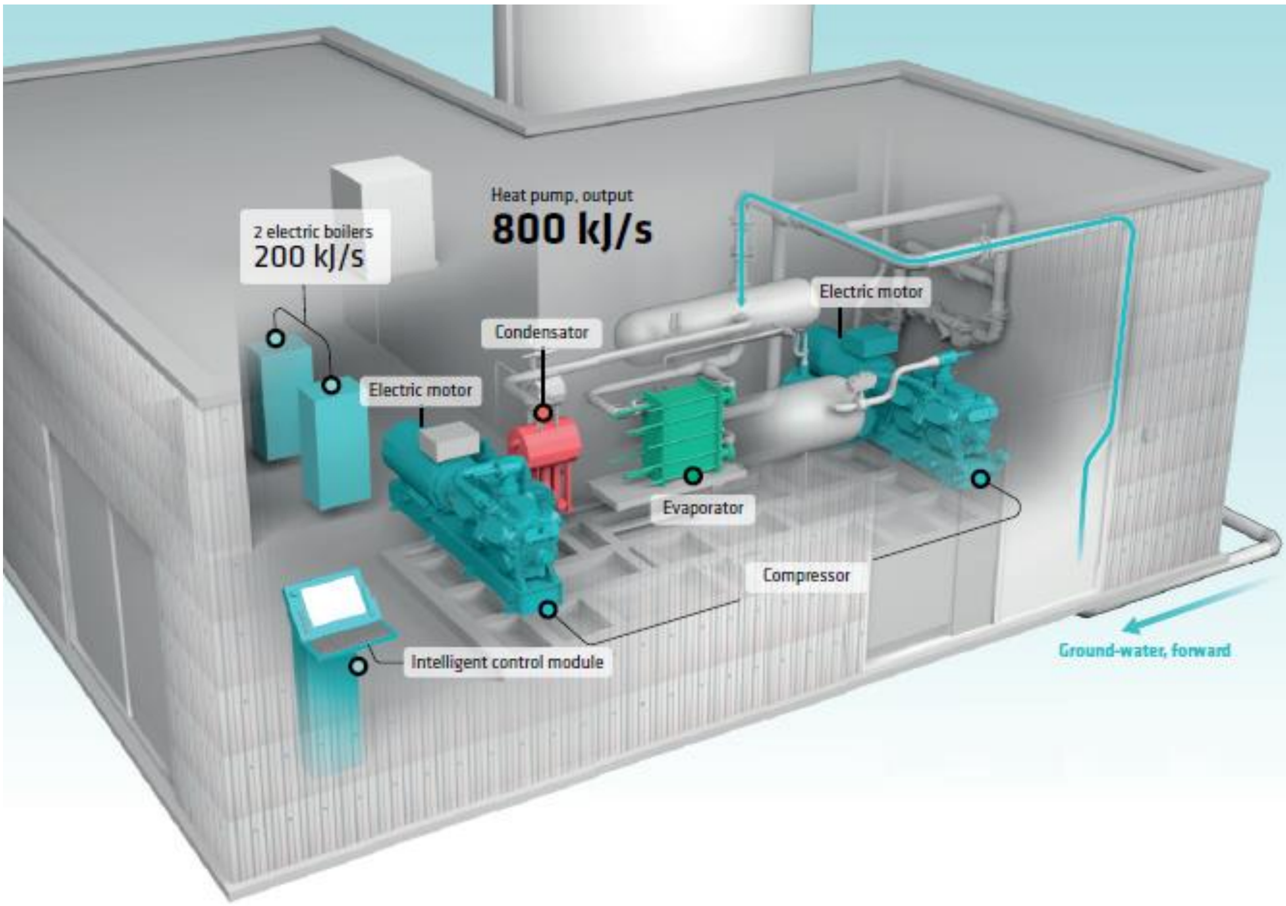


Figure 4: 3D model of the FlexHeat facility.

A summarization of the specifications for the FlexHeat facility are the following:

- 800 kJ/s two-stage heat pump as the primary heat supply
- 2x 100 kJ/s electric boilers as secondary heat supply, ensuring increased flexibility
- A 100 m^3 stratified heat storage tank with a storage potential from 4-5 MWh
- The heat pump has a minimum heat production level of 34 %

The heat pump is intelligently optimized to take advantage of low electricity prices and electricity distribution tariffs by utilizing optimization models with MPC-solvers to plan the heat production at lowest possible costs. Time-shift of heat production is viable at this facility due to the flexibility from the district heating system at the storage tank, grid and consumers.

Furthermore, the facility has been redesigned to deliver fast-regulation services to the TSO-grid. 50 % of the capacity can be regulated within 90 seconds – this is sufficient to provide normal frequency regulation services to the TSO-grid, the FCR-N service.

This heat pump thus has a lot of flexibility to offer the local distribution grid as well but is also constrained by the required heat supply for the consumers, which consumes 300-400 kJ/s in winter periods. This facility will be thoroughly tested in this WP to examine the signaling of a DSO need, the market-based communication with imbalances for the BRP, real-time communication of limitation of the facility and the economic consequences for the facility due to limitations.

2. Test setup

2.1 Prefeasibility study

In EnergyLab Nordhavn, HOFOR and Radius had a use-case named "Timed load-shift for electricity overrun" in which the FlexHeat facility was utilized to handle a simulated electricity overrun for the DSO-grid caused by excessive feed-in from PV and wind turbines.

The tests were performed in a foreseen scenario and an unforeseen scenario.

In the foreseen scenario, the period of overrun was known 24-hours ahead, which enabled HOFOR to prepare the district heating system for increased consumption. Here, the heat supply for the tank, grid and consumers was decreased to a minimum acceptable level beforehand and within a 2-hour reservation period, the heat pump and electric boilers could perform a maximum electricity consumption for the duration.

In the unforeseen scenario, no preparation prior was performed, and the system could deliver a lower amount of electricity consumption in the duration due to a smaller flexibility margin.

These tests were utilized to generalize the costs for delivering services to the DSO-system divided into upwards regulation and downwards regulation for a set of scenarios. These are summarized on Figure 5.

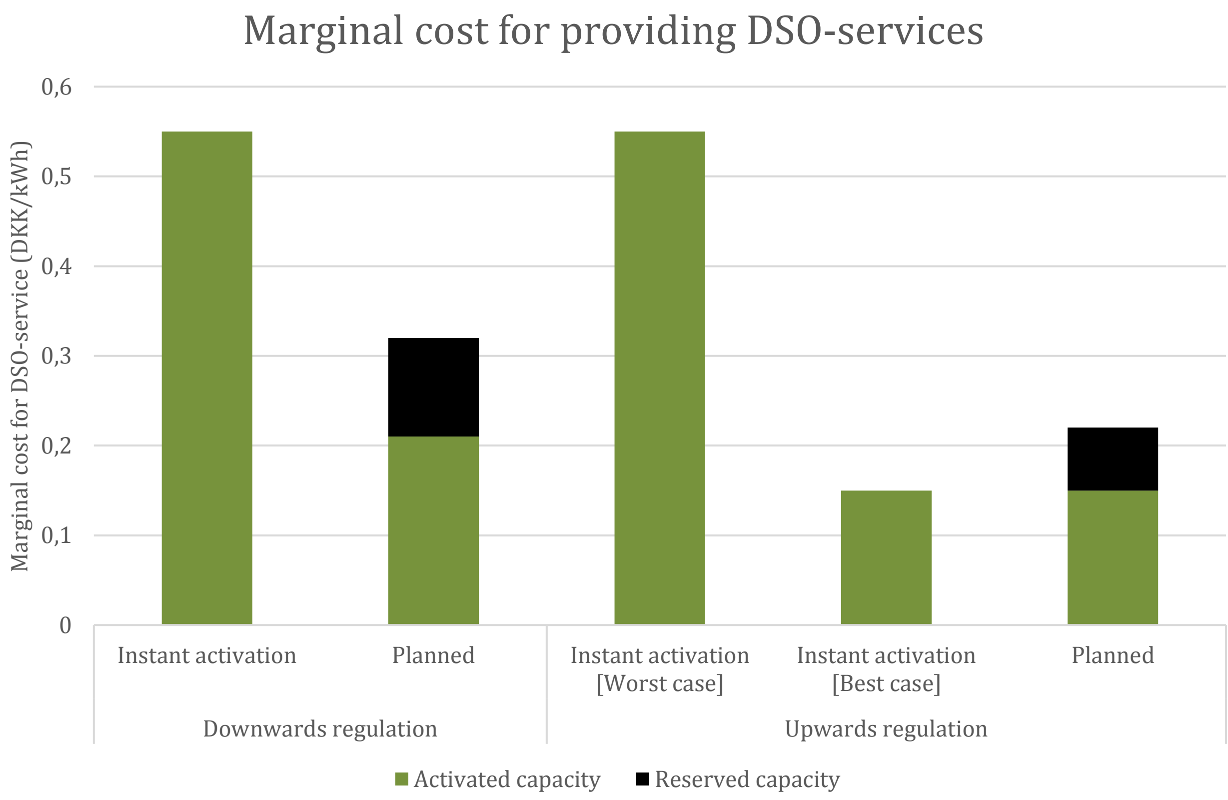


Figure 5: Generalization of marginal costs for providing DSO-services in different scenarios for upwards- and downwards regulation.

For downwards regulation, the electricity overrun could be handled in a planned and an instant activation.

In the planned, the system is prepared 24 hours ahead, and thus there is a cost associated with running the system in a less optimal manner for electricity prices and tariffs. The costs in the activated capacity is significantly lower than for instant activation, as a higher share of the capacity is delivered by the heat pump and not the electric boiler. The storage tank is used as a balancing component between the primary side (heat pump) and the secondary side (consumers) – the heat pump has a minimum heat production level of 34 %, and the tank is needed to balance this production if the consumers have a lower consumption. The electric boiler, on the other hand, will always be able to boost in the mentioned modes, hence if no capacity is reserved, the share of downwards regulation performed by the electric boilers will increase, providing a higher marginal cost for the service.

For the upwards regulation, two scenarios have been defined – a worst-case and a best-case. In the upwards regulation, all electricity consumption is shut down at FlexHeat besides a minimum consumption for ancillary systems. In the best-case, the heat pump is shut down at times which the tank can supply heat for the consumers, thus the only economic consequence is loss in a non-optimal heat production plan, issuing a higher electricity cost. In the worst-case scenario, the heat capacity in the storage tank is insufficient to supply the consumers, forcing a manual start-up of the

back-up oil boilers – this has a high start-up cost and an expensive heat production cost due to the fuel.
In the planned scenario, the minimum level of the storage tank has been increased from 20 % to 50 %, which ensures, that the system can sustain an interruption without the need for oil boilers.

The recommendations from the work here was that a 24-hours ahead reservation of capacity for upwards- and downwards regulation services to the DSO would be the most sensible in regard to economy and risk.

The scenarios depicted in the use-case are for binary operations, i.e. full available capacity for upwards- and downwards regulation. In the field-tests, limitations are explored as a more realistic DSO demand for these services – and here, the focus is solely on upwards regulation services.

2.2 Demand for the DSO

In order to create a relevant test signal, a foreseen and unforeseen scenario for capacity limitation from the DSO is required. In this case, the signal is transmitted via the TPS/dynamic information broker and via BRP to the FlexHeat system. The DSO request to FlexHeat is based on a model for the demand and a congestion situation in the distribution feeder where FlexHeat is connected. The detailed model of how this signal is created is described in d7b.

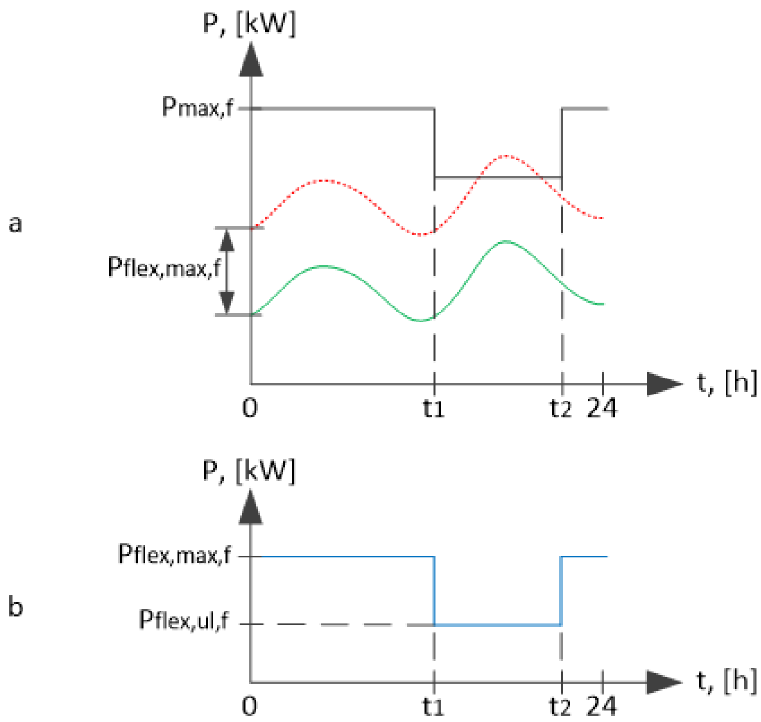


Figure 6: Capacity limitations imposed by the DSO. a – power consumption on a feeder: green curve – consumption from non-flexible loads, red dotted curve. b – total consumption of non-flexible and flexible loads

Figure 6 illustrates the capacity limitations imposed by the DSO on the operation of the flexible loads controlled by AGR.

A detected/forecasted expected feeder overload (hereinafter: “congestion”) is then translated to a capacity limitation applicable to FlexHeat. FlexHeat connected capacity is assumed to be 250kW and a limitation then reduces this value to the remaining available capacity. An example of the resulting limitation is illustrated in Figure 8. The capacity of the entire facility is 450 kW, but the system rarely operates above 250 kW, as the heat demand is lower than 800 kJ/s and the maximum temperature from the heat pump is 84 °C – this is sufficient for any experienced case in the FlexHeat grid.

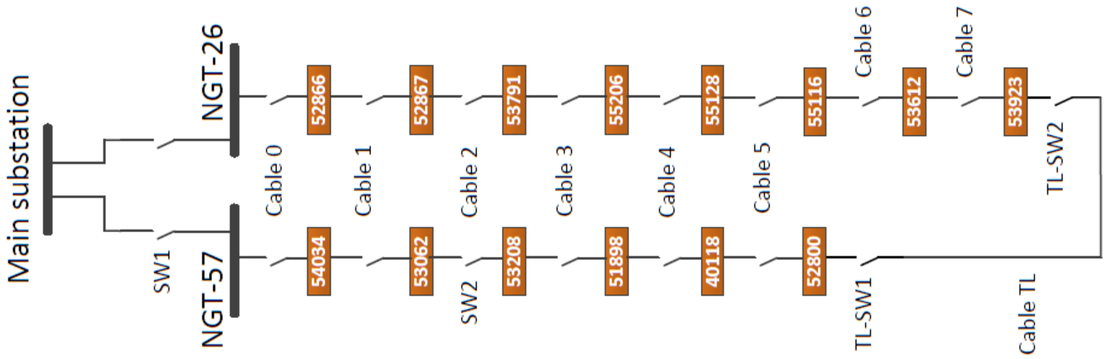


Figure 7: Schematic picture of the loop design in Nordhavn distribution network, boxes denote secondary substations. FlexHeat is connected at feeder 55128.

The model for simulating power congestions consists of one loop with two feeders shown in Figure 7. First, power demands for each cable are calculated to determine their available power consumption. After that, the fault is simulated by randomly selecting the fault’s location, time of occurrence and time of clearance. After the fault occurs, the network is reconfigured in the way that all loads upstream from the fault are supplied from the original feeder and all loads downstream are transferred to a second feeder of the loop. For the end-to-end test the initial fault downtime is not of interest, so the congestion signal is based on the reconfigured feeder alone. The model considers the position of the FlexHeat and does not generate capacity limitations, if limiting FlexHeat will not reduce power congestion (i.e. FlexHeat is not on congested feeder).

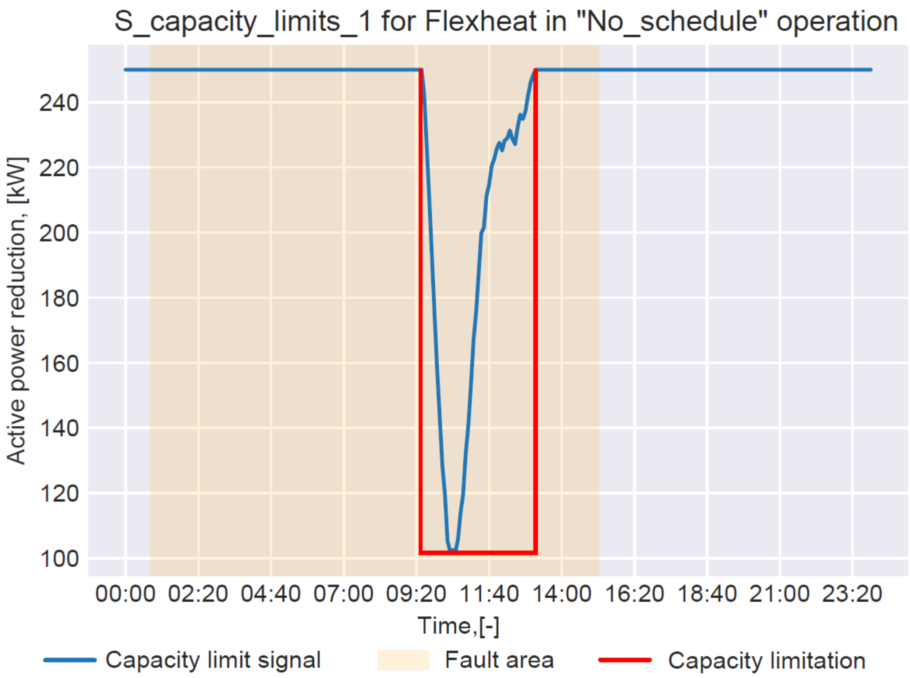


Figure 8: Capacity limitations

The resulting “Capacity Limitation” signal has been recorded as .csv file and corresponds to the content of a TPS/dynamic information broker message to be forwarded to the BRP. The details of TPS message generation and transmission are discussed in D7b.

2.3 Setup for the BRP

In the intersection between TSOs and flexibility assets, BRPs facilitate aggregation and disaggregation of bids and schedules to TSOs and carries out dispatch to flexibility assets. There persist no standards for BRP systems, thus they are based on each BRPs own solutions for services and productions.
However, standards for interfaces towards TSOs, markets, exchanges and flexibility assets are present and adopted by each BRP.
The DREM delivery platform utilizes the following standards for BRP communications:

- **IEC 61850** for real-time data exchange towards flexibility asset
- **IEC 62325** for market-based data exchange towards TPS

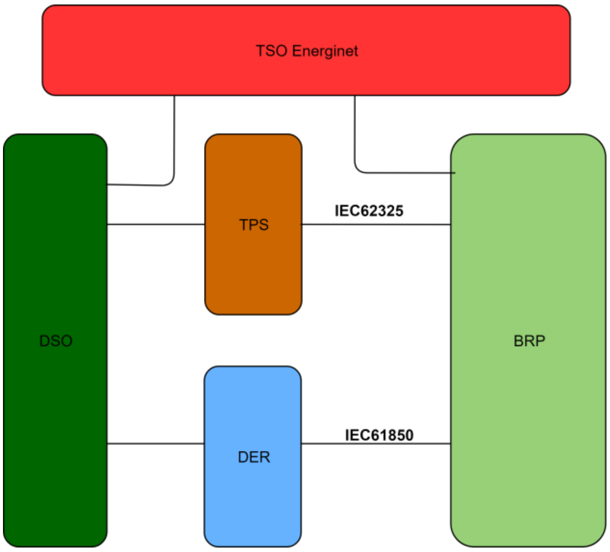


Figure 9: BRP interfaces

The interfaces from the BRP is seen on Figure 9 and the associated communication. Markedskraft has developed its own BRP system, MKPlanner, which real-time communicates with flexibility assets and TSO Energinet. In addition, MKPlanner provides flexibility asset facility managers ability to monitor their flexibility assets in all markets with a graphical user interfaces, which also serves as a platform for submitting electricity market bids and schedules to spot and ancillary service markets.
On Figure 10, MKPlanner user-interface for HOFOR FlexHeat is shown. The green graph marks the consumption plan related to the 4th of march. The red graph shows the spot price.

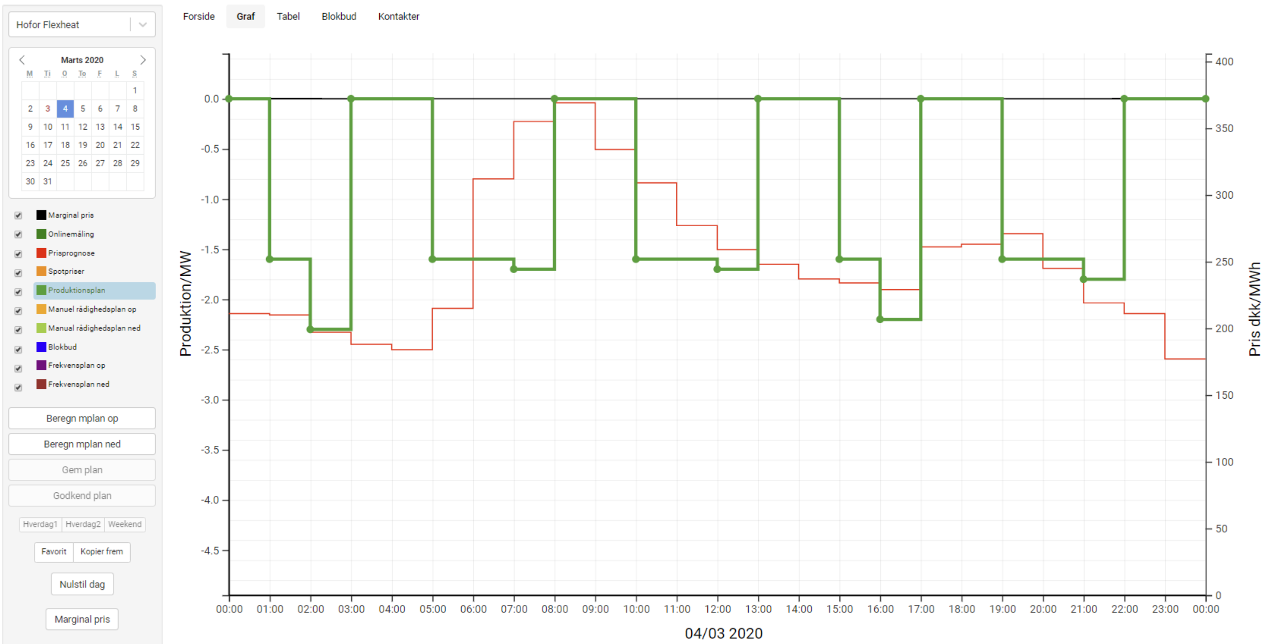


Figure 10: Overview of the FlexHeat schedule on the 4th of March seen from the BRP perspective.

The MKPlanner data model structures flexibility assets as separate entities and binds various systems tags to a specific unit. This allows for separate control of units on MW level for

aggregation and disaggregation.
Dispatch and control of units is handled on specific units and communicated using IEC61850. This abstract data model is shown on Figure 11.

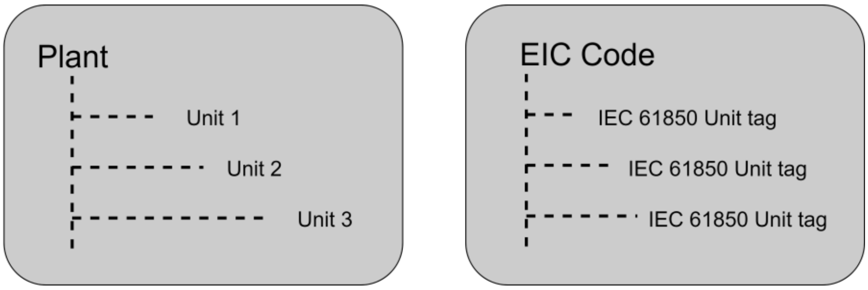


Figure 11: Plant data modelling

The IEC61850 information model is adopted for flexibility assets with plant mapping with EIC Codes and unit mapping using IEC61850 tags.

Monitoring plants in MKPlanner

When flexibility asset schedules reach start, MKPlanner utilizes real-time measurements of unit power output together with the scheduled plan. Real-time measurements assist the control room in Markedskraft to monitoring each customer individually.
The individual customers are monitored and is shown on Figure 12 with IEC61850 real-time measurements. Production plans (green plan) together with online measurements (red graph) on Figure 13.

Setpunkt	-1.6	N/A
Fjernkontrol	Enhed er i fjernkontrol	04/03 - 2020 kl. 15:10
Alarm	Ingen alarmer for enheden	06/12 - 2019 kl. 08:24
Drift	Enheden er i drift	N/A

Figure 12: Real-time measurements from the facility

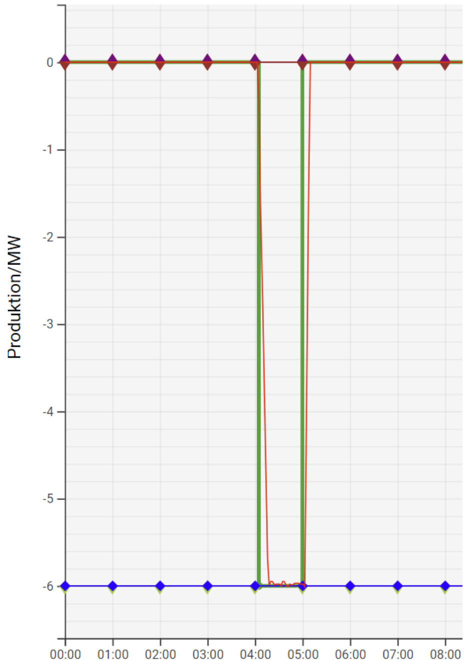


Figure 13: Production plans coupled with live data metering from the site.

BRP & Capacity limitations plans

The delivery model for DREM materialized as a communication scheme, as seen on Figure 1 and 2 in section 1.1, with interfaces to and from TPS and introduces the BRPs as recipient of capacity limitations plans on plant unit level.

It was a perquisite in the delivery model discussion to notify BRPs when changes happen to their balance, next it seemed obvious to let BRPs handle this as they already control the flexibility assets. This is imperative for BRPs to have this signal, as it otherwise would pollute the balance and leave questions of DSO congestion management unanswered.

Any handling of this would be a reactive process and handled subsequent the next day or month in the balance settlement process. When realising the potential of BSPs and multi-BRPs on a grid connection point this becomes increasingly important.

Capacity limitations are expected to alleviate this by supplying BRPs real-time with updated information through the TPS.

The proposed solution is to carry out the capacity limitation on BRP level with the utilization of MKPlanner.

MKPlanner and Capacity limitations plans

The TPS delivery of capacity limitations plans describes a data model with 5-minute resolution with ranges of limitations as absolute maximum grid load for a unit. This provided the opportunity to merge 5-minute MKPlanner schedules with the capacity limitation plans in order to determine which 5-minute intervals needed correction. Effectuation of capacity limitation is carried out by merging these, as seen on Figure 14. A step-wise illustration of the process is seen in Appendix A. This was developed as an experimental feature around MKPlanner test-environment using APIs for MKPlanner and TPS interfaces.

A few requirements were set in the process:

- Handling foreseen and unforeseen as different scenarios.
- No direct limits are set foreseen (day-ahead), instead it is sent to plant facility managers SCADA using IEC 61850
- When receiving limitation intraday, immediately carry out limitation instant
- Updated schedules are sent automated to TSO Energinet
- Only consumption plans are considered for the setup
- Logging of activity

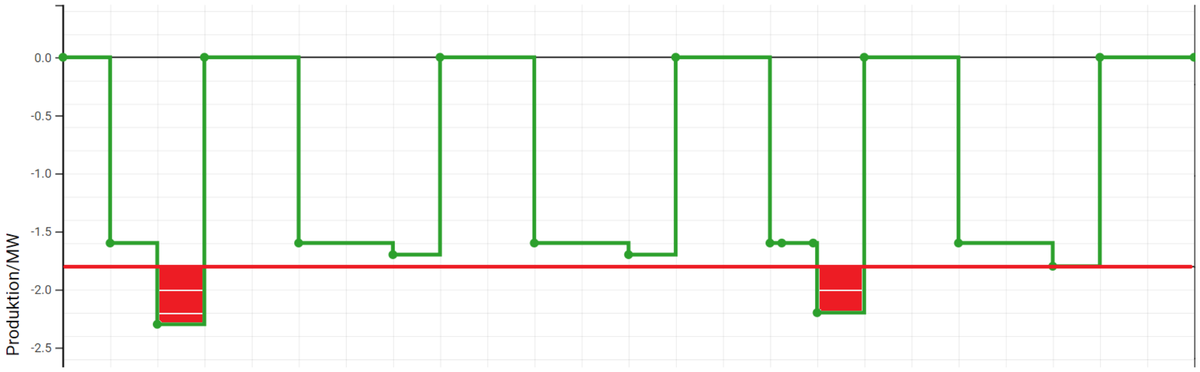


Figure 14: MKPlanner schedule with 1.8 MW absolute grid load capacity with, marked with red, areas for congestion management using capacity limitation plans from TPS

MKPlanner test setup

Creating the test environment around simulated WP7b congestions, capacity limitation plans, MKPlanner, Energinet and FlexHeat, a set of Python-scripts and APIs was utilized. On Figure 15, the structure for data communication in the test is shown – this can be summarized in the following steps:

1. WP7b delivered as .py file with .csv output (As described in section 2.2)
2. Markedskraft Python-script steps
    a. Fetching WP7b capacity limitation plans in .csv file
    b. Determine foreseen and unforeseen congestion management
    c. If foreseen:
        i. Send capacity limit plans to HOFOR
    d. If unforeseen:
        i. Fetching current consumption plans from HOFOR in MKPlanner
        ii. Matching 5-minute schedules with limitations and sending to MKPlanner
        iii. Structuring output to plant and delivering to HOFOR
        iv. Activating endpoint in MKPlanner to send schedules to plant and Energinet

This facilitates the WP7a/b testing. Testing is carried out real-time with no manual process involved, other than initiating the test from a python-script.

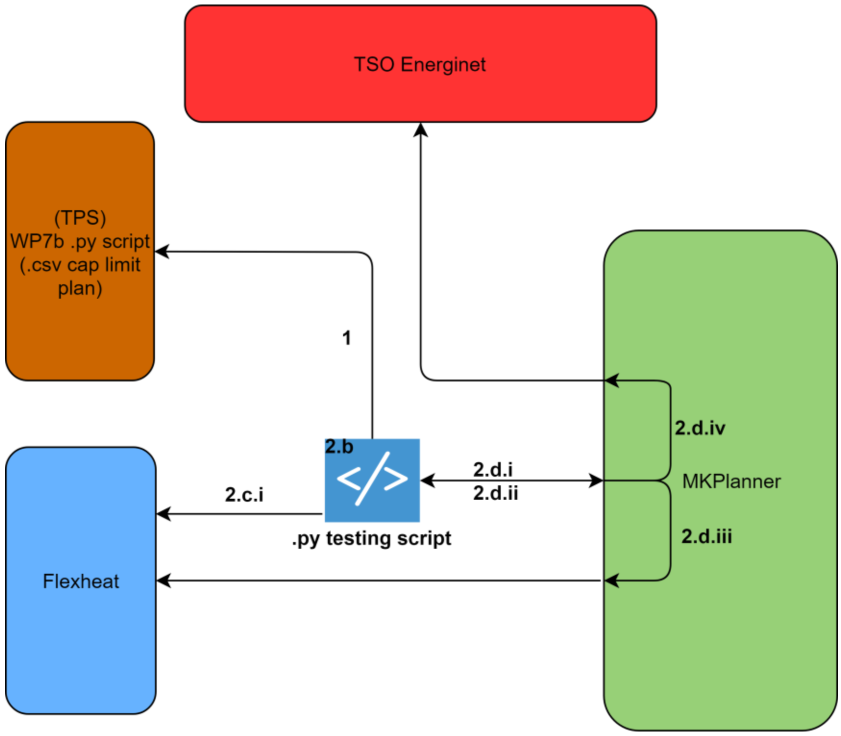


Figure 15: WP7a/b testing environment using MKPlanner test environment and python-script.

2.4 Infrastructure for data communication

The data communication is divided into three streams:

- Communication of plans between the BRP and facility
- **IEC 61850** for real-time data exchange towards the facility
- **IEC 62325** for market-based data exchange towards the BRP

In the communication between the facility and BRP, the BRP tool MKPlanner is used as described in 2.3. This communication constitutes the exchange of plans in the test setup.

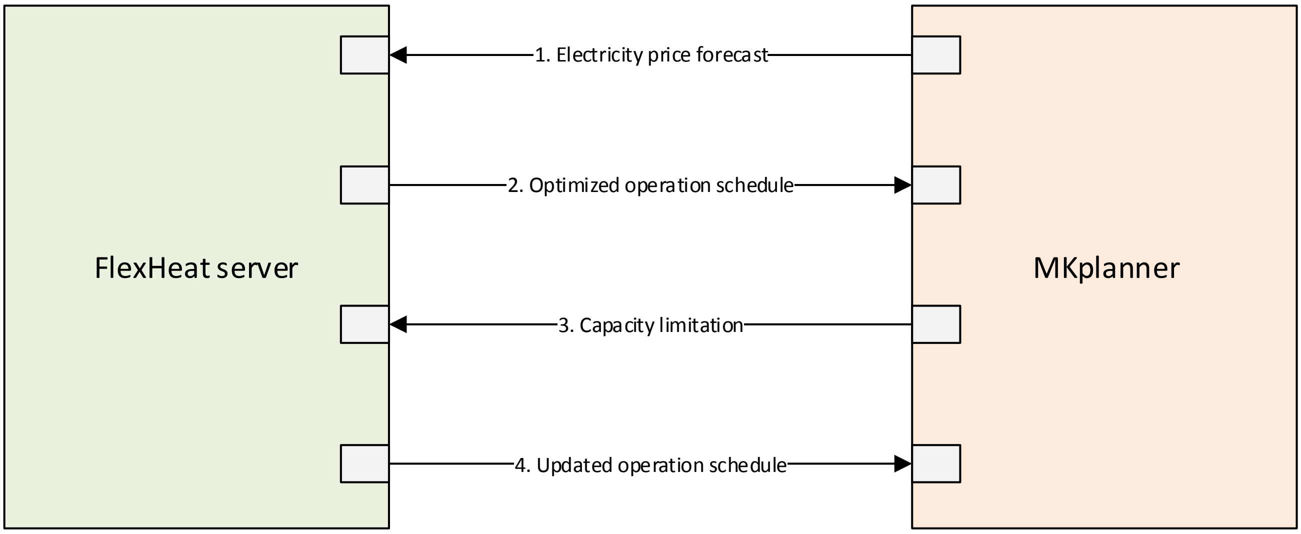


Figure 16: Simplified figure for communication flows between the facility and BRP for exchange of plans.

In Figure 16, the flows for communication are shown between the facility and BRP when exchanging plans.

1. Firstly, electricity price forecast is delivered to HOFOR for the next 48 hours. An additional option could also be to deliver FCR-N price forecasts.
2. Secondly, these are utilized in an optimization model of the FlexHeat system, which schedules an optimal pattern for electricity consumption given the demand situation in the area. This optimization performs a 48-hour optimization but only utilizes the next 24 hours – this is done in order to find the optimal level in the storage tank for the coming days as well. These are delivered to the BRP.
3. Next, the BRP delivers a capacity limitation plan based on the demand from the DSO described in 2.2. This plan issues how much the facility can use of its maximum capacity for each hour.
4. The optimization model is rerun with the capacity limitation to figure out a new optimal production pattern given the constraints. This updated schedule is delivered to the BRP and afterwards executed.

In order to facilitate real-time communication between the facility and BRP, EURISCO has deployed a Certified Data Gateway, CDG, between the actors. The exchanged signals are limited to the most important ones:

FlexHeat → MKPlanner

- Electricity consumption (0 – 450 [kW])
- Alarm status (on, off [0,1])
- Operation status (manual, auto [0,1])
- Remote control status (on, off [0,1])
- Online status for HP and EB (on, off [0,1])

MKPlanner → FlexHeat

- Electricity consumption level for HP and EB (0-450 [kW])

In order to perform these, a series of SCADA calculation are performed in 800xA. The most advanced formula is for instructing a specific electricity consumption for the system – this is due to the need for scenario-based instruction of the facility based on the level of allowed electricity consumption – i.e., if the instructions demand 200 kW, the system will operate the heat pump at this level. If the level is below 80 kW, the system will only run electric boilers, as it is below the minimum of the heat pump. These scenario-specific configurations are not implemented at the heat pump facility by default. It is, however, recommended in this project, that the signal lists are kept at a general level, and the programming is performed in the SCADA systems.

MKPlanner power plant communication uses schedules and setpoints. Schedules are pushed from MKPlanner IEC 61850 clients and servers which real-time translate it to operational setpoints for all markets the unit is participating in: spot-market, intraday and ancillary services. This allows for seamless SCADA integration using standardised interfaces.

2.5 Test scenarios

2.5.1 Foreseen setup

In the foreseen setup, the focus is on utilizing day-ahead capacity limitations in the optimization model and the communication between the facility, BRP and DSO. Here, two scenarios are evaluated:

- Scenario 1: Day-ahead planning
- Scenario 2: FCR-N planning

Here, the models are run with and without a capacity limitation to see the consequences by imposing a limitation, and the ability to plan outside of this constraint.
Scenario 1 is based on the original modelling of the FlexHeat facility, whereas scenario 2 is simulated based on the test results for FCR-N capabilities of a heat pump. This is to illustrate the increased economic consequences of interruption in case the flexibility asset is able to provide balancing services to the TSO, hence reflecting the conflict 5 case. (TSO-DSO conflict)

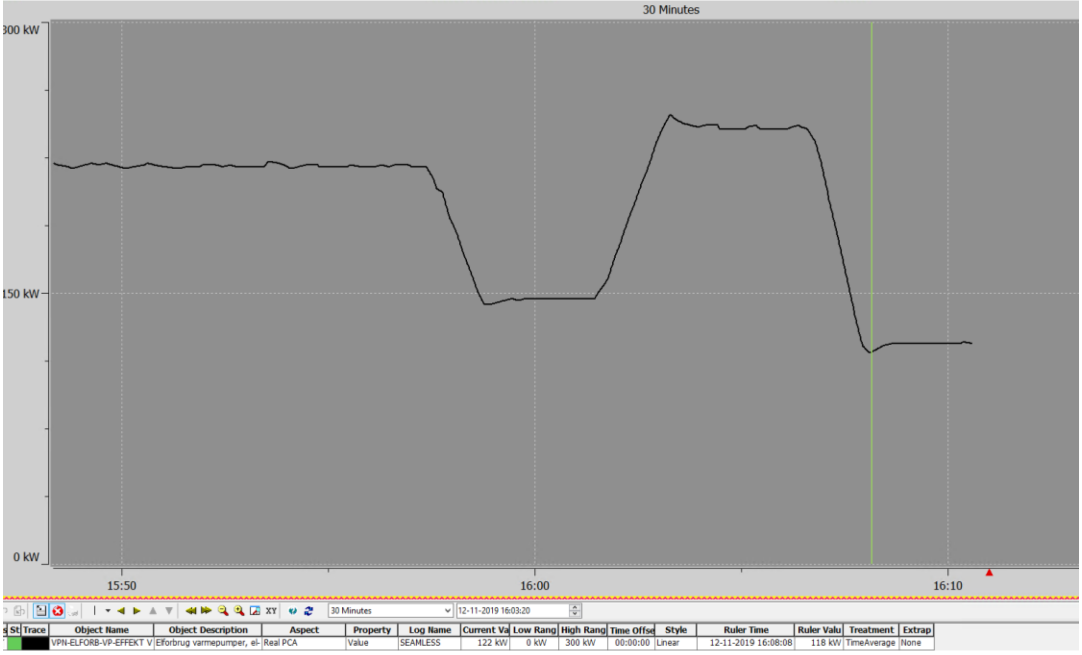


Figure 17: Preliminary test results for FCR-N on the FlexHeat facility

Figure 17 shows the preliminary test results for the FCR-N capability tests on FlexHeat. FCR-N is a frequency containment reserve in DK2, in which it is required to regulate the net frequency in the span from 50,1 to 49,9 Hz. To participate in this market, it is required to deliver a certain capacity within 150 seconds – in the FlexHeat case, this is examined with 50 % of the capacity. Originally, FlexHeat was able to regulate 50 % of its capacity in either an upwards regulation or downwards regulation within 240 seconds. This is too slow for this service, and HOFOR did a reconstruction of the facility and added new components and control techniques in cooperation with Johnson Controls, DTU and COWI. The results are shown in Figure 17, in which the capacity can be regulated within 90 seconds.

This proves that heat pumps are technically feasible to deliver this service. However, this concept still needs to be approved by Energinet when the facility is regulating according to the net frequency. An idealized control of the heat pump power consumption and the net frequency is shown on Figure 18.

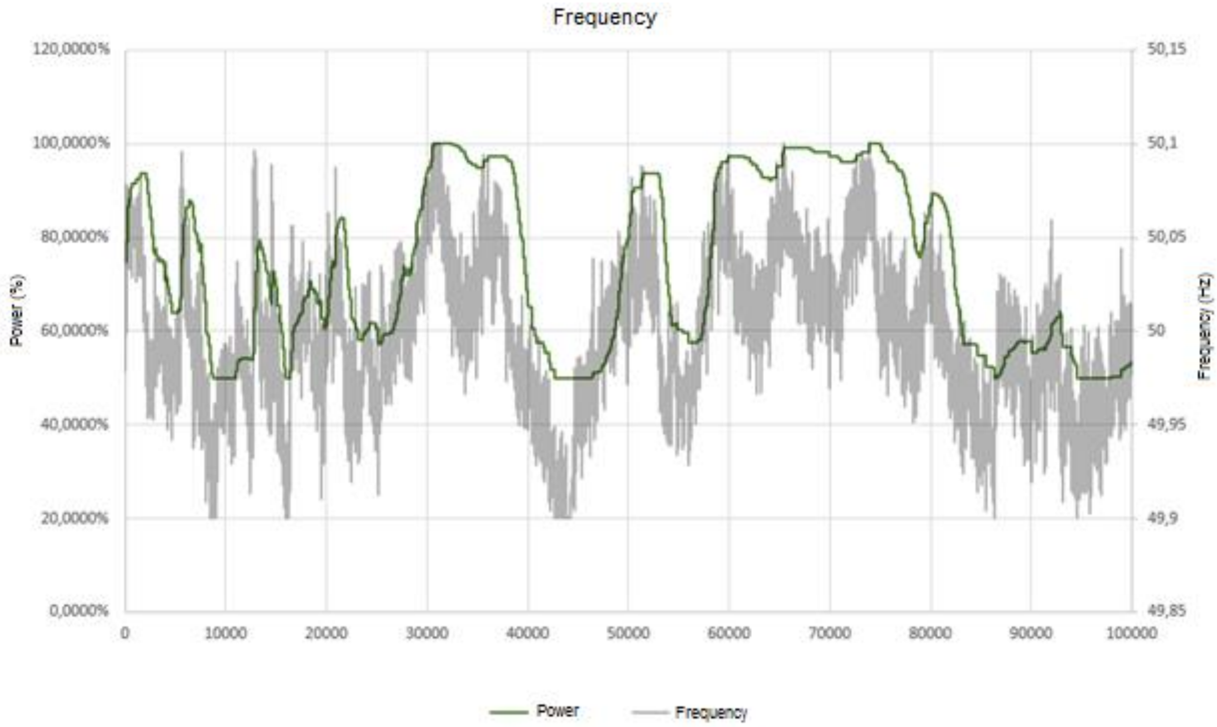


Figure 18: Idealized FCR-N delivery from the FlexHeat facility

Here, the x-axis indicates samples of the frequency. This data is 2 samples a second – resulting in around 13 hours of FCR-N delivery.

To summarize, it is assumed that the facility will be able to deliver FCR-N in a foreseeable future, hence the economic consequences are considered here.

2.5.2 Unforeseen setup

In the unforeseen setup, the same script is utilized at the time, which an unforeseen capacity limitation is being enforced – hence a sudden fault occurs in the system. The plan, which was executed prior to the capacity limitation, is the same as the original plan in the foreseen setup. Here, the hour of capacity limitation is investigated more carefully to assess the technical and economic consequences.

3. Test results

3.1 Foreseen results

Planning phase:

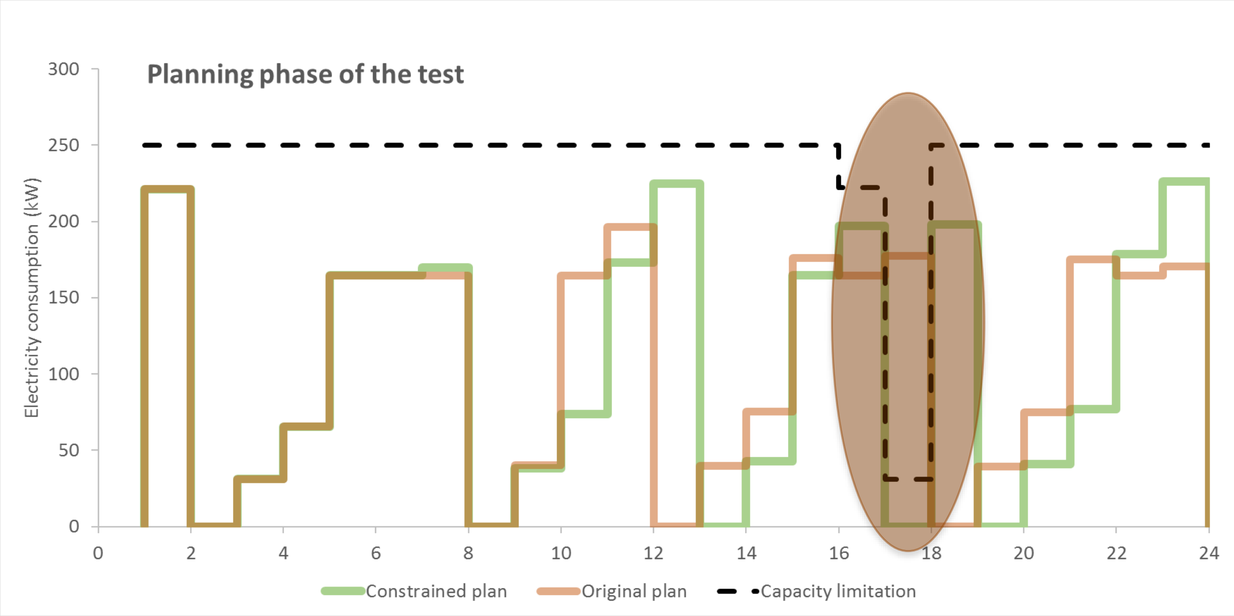


Figure 19: Planning phase of the test.

Figure 19 shows the planning phase of the test – here the most significant capacity limitation is circled. Here, it is evident that the original plan intended on production from the heat pump, whereas the constrained plan increases heat production in the hour before and schedules capacity immediately afterwards.

Test results:

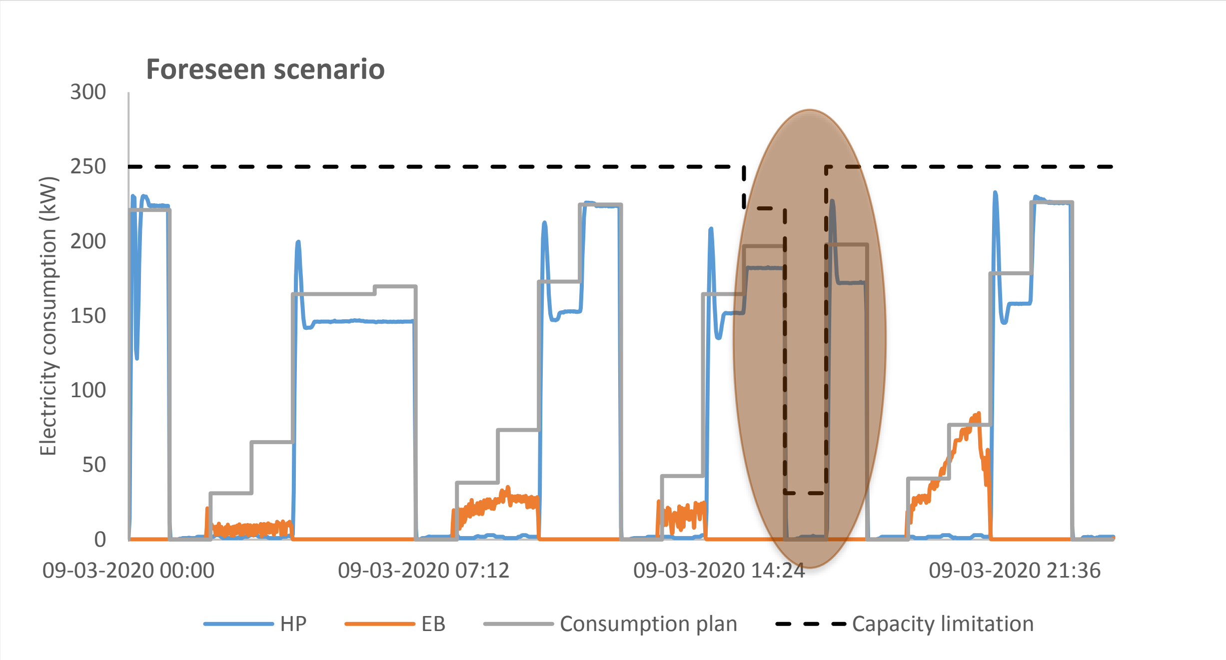


Figure 20: Test results from the foreseen scenario.

Figure 20 shows a 24-hour test with the DREM setup for real-time communication with the heat pump facility. Here, the blue-line is the heat pump consumption and the orange-line are the electric boilers. These are seen compared to the grey-line, which are the consumption plan for the constrained plan, and the capacity limitation plan is shown again as the dotted-black line. Here, the facility successfully shuts down in the constrained hour. There are smaller deviations from the heat pump and electric boiler from the consumption plan, but acceptable for the test. These are smaller optimization for the SCADA calculations received from the BRP. Here, real-time communication proved its value in a production environment.

3.2 Unforeseen results

Output from WP7b Python script can be seen here below – this is a randomized analysis of fault occurrence in the DSO grid in question. The important message here is when the fault occurs and the down-time associated – these are marked in red.

['Brown loop is considered']
Congestion at feeder Secondary_feeder_NGT_26_to_feeder_NGT_57 in Cable_0 at representative day 4
Congestion at feeder NGT_26 in Cable_0 at representative day 4
Congestion at feeder Secondary_feeder_NGT_26_to_feeder_NGT_57 in Cable_0 at representative day 13
Congestion at feeder NGT_26 in Cable_0 at representative day 13
Congestion at feeder Secondary_feeder_NGT_26_to_feeder_NGT_57 in Cable_0 at representative day 14
Congestion at feeder NGT_26 in Cable_0 at representative day 14
['Fault index is 3']
['Fault is on feeder NGT_57 at cable 3']
['Fault time index is 183']
['Fault occurs at 15:15']
['Initial downtime due to the fault is 40 minutes']
['System is reconfigured at 15:55']
['System restored at 16:55']
Congestion at feeder Secondary_feeder_NGT_26_to_feeder_NGT_57 in Cable_0 at representative day 0

Congestion at feeder Secondary_feeder_NGT_26_to_feeder_NGT_57 in Cable_0 at representative day 4
Congestion at feeder NGT_26 in Cable_0 at representative day 4
Congestion at feeder Secondary_feeder_NGT_26_to_feeder_NGT_57 in Cable_0 at representative day 13
Congestion at feeder NGT_26 in Cable_0 at representative day 13
Congestion at feeder Secondary_feeder_NGT_26_to_feeder_NGT_57 in Cable_0 at representative day 14
Congestion at feeder NGT_26 in Cable_0 at representative day 14

A graphic illustration of this can be seen on Figure 21.

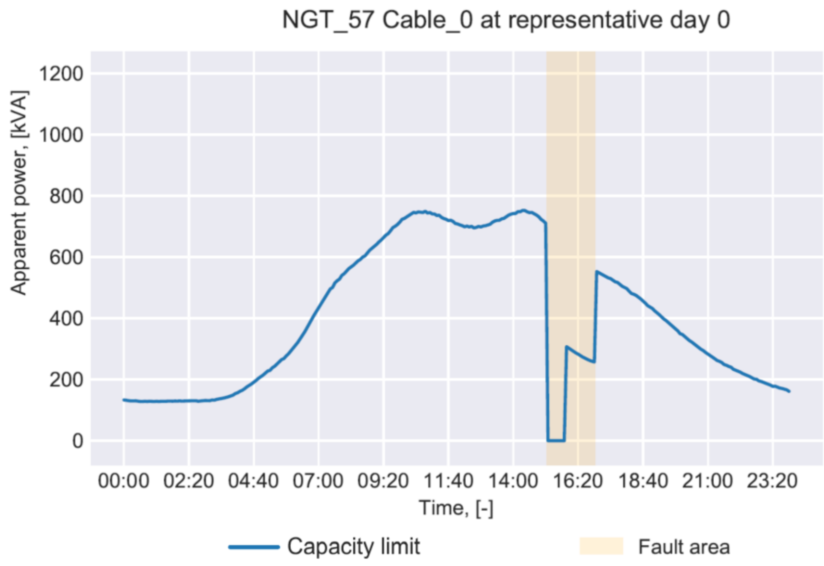


Figure 21: Capacity limitation from the DSO script.

MKPlanner schedule, handled day before and traded on Nordpool in spot market. This is shown on Figure 22.

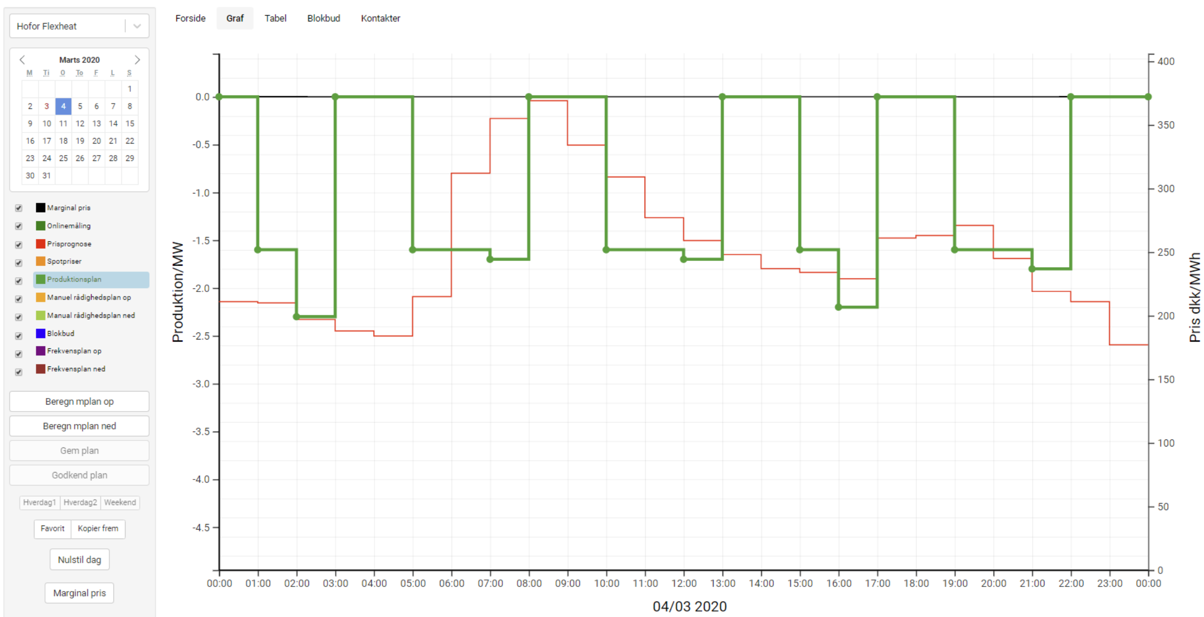


Figure 22: Original plan in MKPlanner for the 4th of March.

An example of the real-time data communication can be seen on Figure 23. Here, the BRP is informed what setpoint the facility is currently operating after, whether the facility can be remote controlled, if there are any alarms on the facility and whether the heat pump and/or electric boilers are operating or not.

Setpunkt	-1.6	N/A
Fjernkontrol	Enhed er i fjernkontrol	04/03 - 2020 kl. 15:10
Alarm	Ingen alarmer for enheden	06/12 - 2019 kl. 08:24
Drift	Enheden er i drift	N/A

EIC45W000000000115P_HD1EB1/MMXU1.TotW.mag.f	2020-03-04 14:...	2020-03-04 14:...	0.1412	NULL

Figure 23: Real-time data communication between the DER and the BRP during tests.

The capacity limitation, which is produced in real-time from the script 2.2 and d7b, supplies the limitation seen on Figure 24.

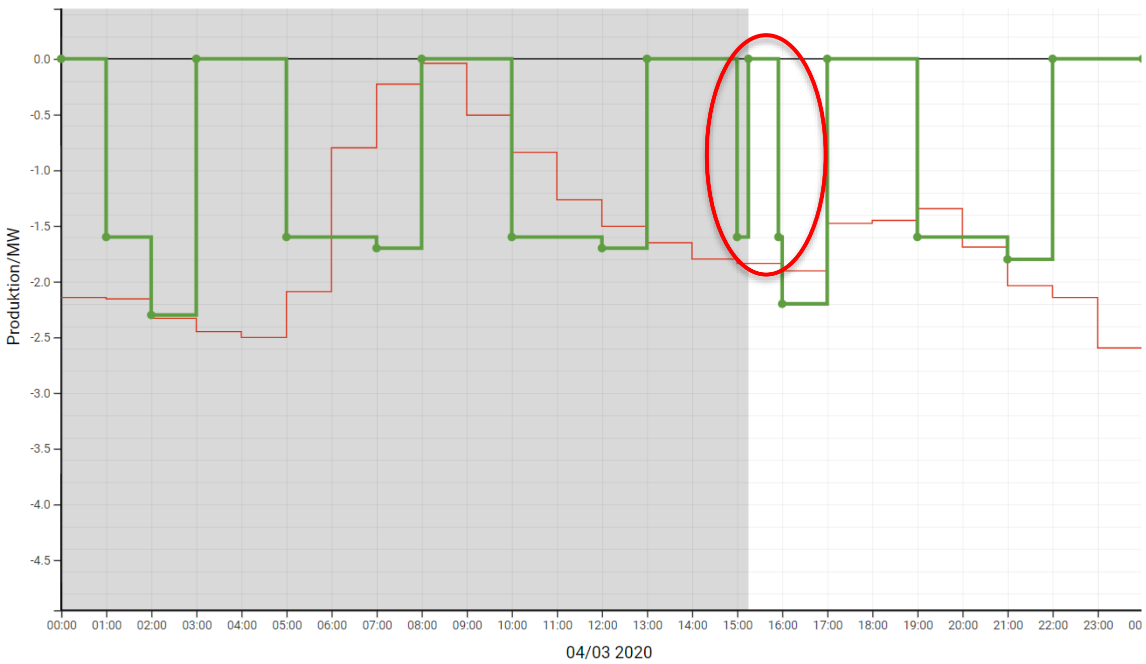
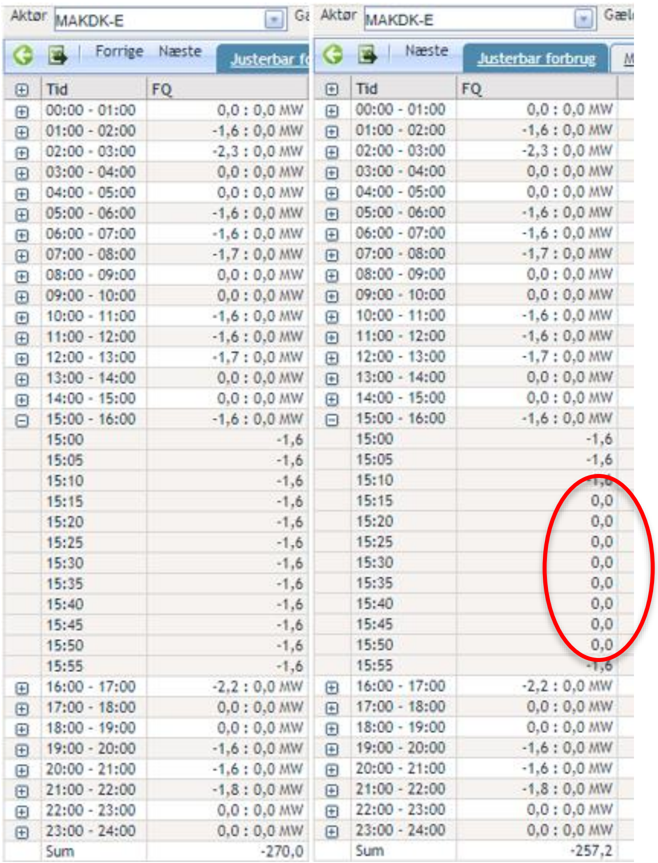


Figure 24: Unforeseen limitation imposed on the flexibility asset.

Furthermore, the imposed plan from the BRP and the real-life measurements from the site is shown on Figure 25. Here, the intelligent module on FlexHeat follows the plan somewhat closely throughout the period with smaller deviations. Here, the orange marked area indicated the imposed constraint from the BRP on the facility.

Figure 25: Data from the FlexHeat facility compared to the original plan and the unforeseen capacity limitation.

Signals to the TSO



Aktør MAKDK-E | Gæ… — Forrige Næste Justerbar f…

Aktør MAKDK-E | Gæl… — Næste Justerbar forbrug M…

Tid	FQ	FQ
00:00 - 01:00	0,0 : 0,0 MW	0,0 : 0,0 MW
01:00 - 02:00	-1,6 : 0,0 MW	-1,6 : 0,0 MW
02:00 - 03:00	-2,3 : 0,0 MW	-2,3 : 0,0 MW
03:00 - 04:00	0,0 : 0,0 MW	0,0 : 0,0 MW
04:00 - 05:00	0,0 : 0,0 MW	0,0 : 0,0 MW
05:00 - 06:00	-1,6 : 0,0 MW	-1,6 : 0,0 MW
06:00 - 07:00	-1,6 : 0,0 MW	-1,6 : 0,0 MW
07:00 - 08:00	-1,7 : 0,0 MW	-1,7 : 0,0 MW
08:00 - 09:00	0,0 : 0,0 MW	0,0 : 0,0 MW
09:00 - 10:00	0,0 : 0,0 MW	0,0 : 0,0 MW
10:00 - 11:00	-1,6 : 0,0 MW	-1,6 : 0,0 MW
11:00 - 12:00	-1,6 : 0,0 MW	-1,6 : 0,0 MW
12:00 - 13:00	-1,7 : 0,0 MW	-1,7 : 0,0 MW
13:00 - 14:00	0,0 : 0,0 MW	0,0 : 0,0 MW
14:00 - 15:00	0,0 : 0,0 MW	0,0 : 0,0 MW
15:00 - 16:00	-1,6 : 0,0 MW	-1,6 : 0,0 MW
15:00	-1,6	-1,6
15:05	-1,6	-1,6
15:10	-1,6	-1,6
15:15	-1,6	0,0
15:20	-1,6	0,0
15:25	-1,6	0,0
15:30	-1,6	0,0
15:35	-1,6	0,0
15:40	-1,6	0,0
15:45	-1,6	0,0
15:50	-1,6	0,0
15:55	-1,6	-1,6
16:00 - 17:00	-2,2 : 0,0 MW	-2,2 : 0,0 MW
17:00 - 18:00	0,0 : 0,0 MW	0,0 : 0,0 MW
18:00 - 19:00	0,0 : 0,0 MW	0,0 : 0,0 MW
19:00 - 20:00	-1,6 : 0,0 MW	-1,6 : 0,0 MW
20:00 - 21:00	-1,6 : 0,0 MW	-1,6 : 0,0 MW
21:00 - 22:00	-1,8 : 0,0 MW	-1,8 : 0,0 MW
22:00 - 23:00	0,0 : 0,0 MW	0,0 : 0,0 MW
23:00 - 24:00	0,0 : 0,0 MW	0,0 : 0,0 MW
Sum	-270,0	-257,2

Figure 26: Signals to the TSO

On Figure 26, the non-congested plan is shown on the left-hand side, and the congested plan on the right-hand side. Here, the red-circled area is the capacity limitation for the site. This is shown to illustrate how the BRP signals a capacity limitation to the TSO and will thus increase valuable communication between the actors of the electricity markets in a DSO congestion situation.

4. Analysis

4.1 Consequences in the foreseen scenario

4.1.1 Economic evaluation

A specific scenario was shown in the foreseen test in 3.1. To calculate more generally, 5 scenarios were generated from the script mentioned in 2.2 based on the work in d7b. These are shown on Figure 27.

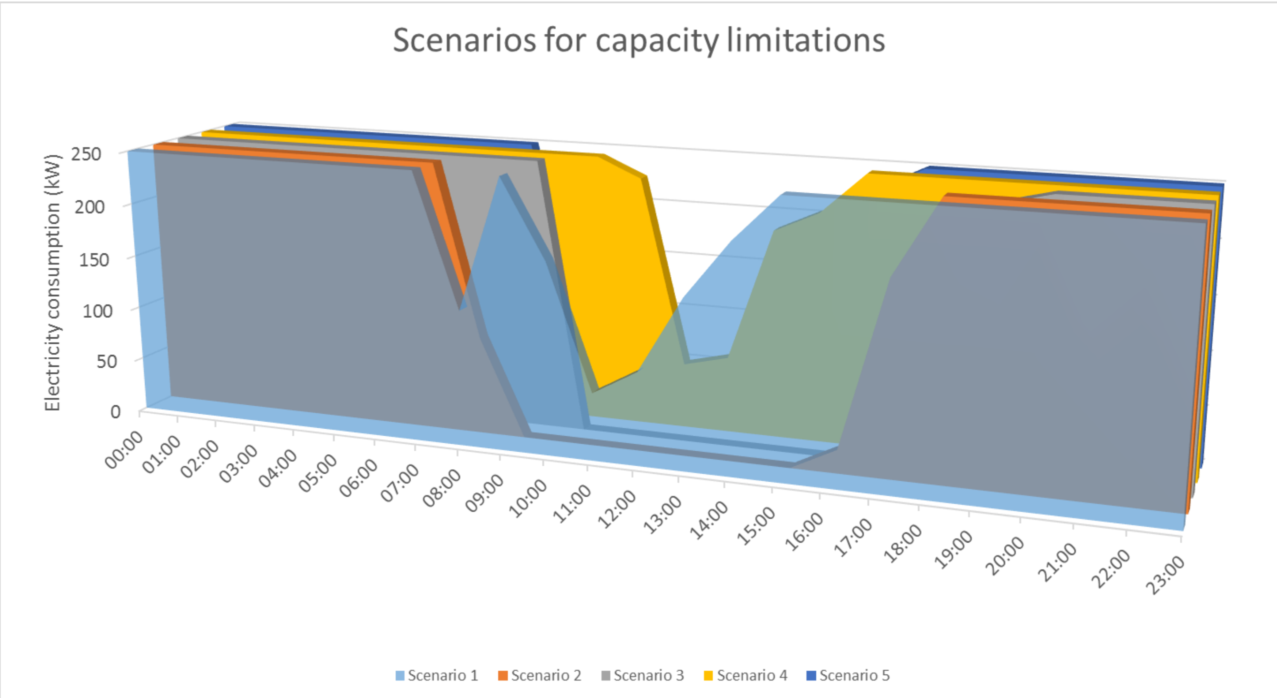


Figure 27: Scenarios for capacity limitations - here, 5 scenarios have been produced from the script developed in d7b.

These scenarios are computed with the optimization model to evaluate the total costs for heat production.

Day-ahead results:

Here, the same plan has been rerun with 5 different scenarios for capacity limitations, which are then compared to the original plan. The original plan yielded a heat production cost of **232,87 DKK/MWh.**

	Heat costs *[DKK/MWh]*	Change in heat costs *[%]*
Scenario 1	242,02	3,93
Scenario 2	497,87	113,8
Scenario 3	547,41	135,07
Scenario 4	235,48	1,12
Scenario 5	378,99	62,75

Here, it is evident that more limited plans in scenario 2, 3 and 5 will result in the need to utilize the back-up oil boilers for FlexHeat. This will have significant consequences for the heating costs in the area.

In scenario 1 and 4, the facility is able to utilize the flexibility in the heating system to reschedule heat pump and electric boiler production. This will thus only result in a slightly higher heat production cost.

Ancillary services results:
In this analysis, it is assumed that FlexHeat participates on the FCR-N market and day-ahead market. Here, the reference scenario yields a heat cost of **196,14 DKK/MWh.**

	Heat costs *[DKK/MWh]*	Change in heat costs *[%]*
Scenario 1	198,74	1,32
Scenario 2	448,86	128,85
Scenario 3	520,18	165,21
Scenario 4	196,45	0,16
Scenario 5	342,42	74,58

Here, the changes are higher in scenario 2, 3 and 5, as the general heat cost is lower, and thus usage of oil boilers has a higher influence.
In scenario 1 and 4, the difference is insignificant – this is mostly due to the capacity limitation being enforced in the middle of the day. For the FCR-N prices, the prices are highest during night-time and lowest in the middle of the day, hence the production planned in the limited periods are substantially lower. Night-time interruptions would thus be more significant.

One of the major advantages of performing foreseen capacity limitation is that optimal planning can decrease the marginal costs for DSO capacity limitations. Furthermore, high prices in scenario 2, 3 and 5 can allow the DSO to perform limitations, or more lenient interruptions for this facility.

4.1.2 Technical evaluation

As mentioned in 2.4, there is an additional layer in the communication between the BRP and DSO to facilitate a capacity limitation plan and an additional layer between the BRP and facility.

It makes it relatively easy to communicate plans and reschedule production plans based on the capacity limitation plan. The execution of the plan and the technical considerations here are explained more thoroughly in the unforeseen setup, 4.2.

For the foreseen scenario, more communication between the actors for the planning and improving the logic for the optimization model to include capacity limitation plans have proven successful.

4.2 Consequences in the unforeseen scenario

4.2.1 Economic evaluation

The situation

The economic consequences for FlexHeat in the unforeseen scenario was based on spot market operations being interrupted for hour 16 the 4th of March 2020.
For hour 16, Markedskraft brought 0,16 MWh on DK2 at Nordpool at 268.56 DKK/MWh. The hour saw no balance market regulation.

However, the site was forced to shut-down and start-up again after the hour, whereas the original plan was to continue operation. The model values a start-up cost of the facility at 30 DKK/start-up. This economic key-figure is based on COP loss during start-up, increased O&M and decreased lifetime of the facility.

Hence, the costs are based on a small difference in buying the electricity back at a later point to a less optimal electricity price, and the start-up costs. This would mean a relatively small marginal cost for the DSO-service – however, this is a best-case scenario given no regulation prices and no need for oil boilers. The costs would thus be in the range of **30-80 DKK/MWh**.
In figure 28, the balance prices are shown for the day in question.

EUR/MWh

04-03-2020	Price up	Price down	Dominating direction
00 - 01	58,00	30,10	U
01 - 02	28,10	10,00	D
02 - 03	27,08	10,00	D
03 - 04	26,80	10,00	D
04 - 05	26,80	10,00	D
05 - 06	30,05	10,65	D
06 - 07	36,51	10,65	D
07 - 08	47,20	12,50	D
08 - 09	54,75	54,75	-
09 - 10	50,32	50,32	-
10 - 11	44,23	44,23	-
11 - 12	41,09	41,09	-
12 - 13	37,90	37,90	-
13 - 14	35,97	35,97	-
14 - 15	35,00	35,00	-
15 - 16	35,88	35,88	-
16 - 17	39,50	39,50	-
17 - 18	48,49	48,49	-
18 - 19	64,73	64,70	U
19 - 20	63,37	63,34	U
20 - 21	54,00	43,58	U
21 - 22	47,30	37,53	U
22 - 23	49,00	33,92	U
23 - 00	49,29	31,82	U

Figure 28: Balance prices in the hour of tests.

Worse-case situation

The worst-case situation would be based on the following points:

a) Forced start-up of an oil boiler
b) Forcing an additional start-up of the heat pump
c) Extreme prices for downregulation in the hour
d) High difference in spot price between the interrupted hour and the buy-back hour

With these considered, prices can be relatively extreme. This would yield an additional cost of 30 DKK in a), an additional cost of 900 DKK in b), additional cost of 400,91 DKK in c) and 128,57 DKK in d). This adds up to a total of **1.459,48 DKK/MWh** in a worst-case interruption.

The cost in b) is based on the price for utilizing oil boilers and hourly cost of starting the oil boilers, as they are manually operated. The cost in c) is based on the highest difference between the spot price and downregulation price in 2019, which occurred in hour 16 on the 16th of January. In d), the average spot price for every unique hour throughout 2019 is taken, and the highest spot price difference is utilized here. Here, the lowest price is found in hour 4 during the day and the highest is found at hour 20.

4.2.2 Technical evaluation

For the real-time communication, the following timing has been proven:

- The script from d7b produces a fault at 15:15:00
- The TSO has received an updated plan at 15:15:04
- The FlexHeat receives a plan for 0 kW at 15:15:04
- The FlexHeat facility is consuming 0 kW at 15:17:00

Hence, all relevant actors (flexibility asset and TSO) have received information 4 seconds after the fault occurs, and within 2 minutes, the site is consuming 0 kW as intended.

It has thus been possible to implement proper real-time communication to a flexibility asset while updating plans to the TSO.

4.3 Comparison to the prefeasibility study

The economic costs in the prefeasibility study were assessed to be 550 DKK/MWh in the worst-case situation and 150 DKK/MWh in the best-case situation. This study was a screening based on a downwards regulation test performed in ELN.

The results of 550 DKK/MWh reflect some of the results in the foreseen scenario for longer interruptions, but the unforeseen scenario depicts a significantly higher cost in the unforeseen scenario.

For the best-case scenario, both the foreseen scenario and performed unforeseen test indicates that this can be done cheaper than anticipated. Hence, more extreme situations were found in the experimental and simulation-based results.

5. Conclusions and recommendations

It has been proven technically possible to utilize open standards for data communication – **IEC 61850** for real-time data exchange and **IEC 62325** for market-based data exchange. Furthermore, the real-time data exchange was successfully executed in less than 2 minutes. Real-time data communication with a flexibility asset in a production environment is also an important result as the cyber security of the DREM system has proven adequate.

On the flexibility asset, standardized data communication was deployed to ensure that a total of 4 signals going back and forth were sufficient to control the facility to deliver DSO-services. Site-specific calculations were utilized to ensure that few standardized communication signals would be applicable – these would also be useful for other flexibility asset units.

In the tests, it was shown that conflict case 4 of the TSO-DSO conflict was valid – both for the economic consequences of ancillary services in the foreseen scenario and the data communication to the TSO in the unforeseen scenario. Furthermore, we have also seen how the DSO can counteract aggregation activities by enforcing a constraint, depicting conflict case 5. Conflict case 8 was only depicted in the prefeasibility study, but the setup could as well be utilized for downwards regulation.

The results indicate that unforeseen capacity limitation can have fatal consequences for the costs of delivering DSO-services. The risks of no communication with flexibility asset for interruptions can thus be very high. The foreseen results indicate that the costs can be limited to a minimum, even with longer periods of interruption.

It is thus vital to at least deliver 24 hours ahead signals to ensure that the costs do not accelerate due to imbalances and utilization of oil boilers. These results are only for a specific flexibility asset, and other flexibility assets need to be tested to have a broader view on the economic consequences – however, interruptions of a heat pump in the district heating system could also result in utilization of peak-load boilers.

Important for delivery of DSO-services are to ensure foreseen signals and then the flexibility asset, in this case heat pumps, would be able to supply a quality DSO-service.

6. Perspective

The results from the field-test indicated delivery of DSO-service in a foreseen and unforeseen scenario. In a broader perspective, there are several tools in question to handle these congestions – here the DSO-services could be structured as the following, either demand-response mechanisms or direct-control mechanisms:

- Dynamic tariffs
- Bilateral contract for interruptions
- Market-based DSO-services

The market design is still in question, but the most important finding from d7a is that a foreseen signal is required for properly delivering affordable and quality DSO-services from flexibility assets.

In a future system with 300 MW heat pumps and electric boilers in Copenhagen as an example, the flexibility becomes increasingly important as the expected mix will be larger central units but also a series of decentral heat pumps. Here, fair and transparent signalling for congestion challenges is paramount for enabling the flexibility from the district heating sector towards the electricity system.

7. Appendix A – Markedskraft