HEAT 4.0

Report on Cross System Optimization

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The current report is part of the Innovation Fund Denmark's project[1] ***HEAT 4.0 Digitally-Supported District Heating*** which aims at developing digitally-supported solutions for the district heating sector. The report is presenting one central concept, called Cross System Optimization (CSO), where the objective is to optimize the district heating (DH) system across the entire system by combining individual component optimization tools. In the current report, the concept is explained, solutions are presented and results are assessed in detail. The findings and conclusion of this report are collected and merged with other results by the overall HEAT 4.0 project in a 'Final Report'[2] to the funding organisation, the Innovation Fund Denmark.

To avoid confusion, it is worthwhile mentioning, that there is a step in the CSO development that is not covered by the current evaluation and report. During the development phase, communication across the involved components and software systems was supported by a research cloud, called 'Science Cloud', delivered by DTU[3]. However, it was the plan to replace this temporary cloud with a 'Commercial Cloud', but this happened after the current work was carried out and therefore the effect of this change is not described here. The effect of a commercial cloud is therefore not represented in the current report. But it is a presumption that the commercial cloud will not have any impact on the results as long as this 'common component' or 'common infrastructure' is applied as a data-sharing solution only. In future implementations, this could be changed by additional services by the cloud component e.g. orchestration or optimization delivered by the cloud itself as 'Common Components' or 'Common Solutions'. The commercial cloud was implemented in spring 2022 and it is expected applied on the partner installations during summer 2022, starting with Trefor in Kolding (see below regarding the involved demonstration cases).

The current document is organised as follows: In Section 2 the HEAT 4.0 project and its concepts are introduced, followed by an introduction of the specific district heating cases. The involved cases are applied for development, testing and documentation of results collected in the HEAT 4.0 project. In Sections 3 to 6, each involved company presents their innovations and achievements attached to their software components and their contribution to the cross system optimization solution. Section 7 presents the implementation of CSO as a whole and wraps up the results achieved by this concept. The following Section 8 discusses challenges in business modelling that the CSO concept brings along.

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[1] Innovation Fund Denmark Journal number 8090-00046B
The project homepage can be found on https://www.heatman.dk and scientific results are collected on https://smart-cities-centre.org. The project was funded by the Innovation Fund Denmark under the grant number J.nr. 8090-0046B.

[2] The final report for the whole HEAT 4.0 project will be available at the above homepages. This report is not written at the time of writing the current report, hence the exact title is not decided yet.

[3] Science Cloud for CITIES, Xiufeng Liu and Alfred Heller, Technical University of Denmark (DTU).

List of abbreviation

Please note that most abbreviations are introduced in Section 2.

CSS	Cross System Services
CSO	Cross System Optimization
DH	District Heating
p2p	Peer to Peer
p2c2p	Peer to Cloud to Peer OR Peer to Common to Peer
BRP	Balance Responsible Parties

1. Summary and lessons learned by HEAT 4.0 on Cross System Services

One of the main innovations of the HEAT 4.0 project is the optimization of district heating systems across the whole system, called Cross System Optimization (CSO). Definitions and cases are explained in Section 2. In this first Section 1, experiences and main results of CSO implementation are summarized and applied in three full-scale case studies in Denmark. Readers that see this report for the first time and who are not familiar with the used terminologies will need to find more detailed information in Section 2. You will further find partial summaries formulated by the involved partners in Subsections 3.6, 4.3, 5.3 and 6.5, the overall evaluation of the CSO concept in Section 7 and a few discussions on findings belonging to business subjects in Section 8.

1.1 Generic achievements

HEAT 4.0 and CSO did generate various values for the involved parties and the district heating sector.

A common business concept and infrastructure platform (Precondition for CSO):

- ✓ HEAT 4.0 digital platform: The consortium succeeded in developing and commercialising a HEAT 4.0 digital platform, containing common platform components (e.g. the commercial cloud), protocols and a standard interface (e.g. OPC-UA, REST-API interfaces between components) and others.
- ✓ HEAT 4.0 Commercial Cloud: Center Denmark (partner) is implementing a 'commercial cloud' component/infrastructure for the HEAT 4.0 digital platform that will be ready to handle data exchange between partners in secure and robust way. The service will be available during autumn 2022.
- ✓ HEAT 4.0 Ready: The consortium agreed on a 'HEAT 4.0 Ready' label, illustrating that a given software solution is able to integrate with the HEAT 4.0 digital platform.
- ✓ HEAT 4.0 Science Cloud: DTU (partner) has during the project's lifecycle hosted a common cloud component that is commercialised in the 'Commercial Cloud'. The Science Cloud for CITIES will also in the future be applied for research, innovation, development and educational reasons.
- ✓ Cross System Services (CSS): The consortium succeeded in the development, testing and commercialisation of CSS as an overall concept of cooperative software solution for the district heating (and utility) sector.
- ✓ Cross System Optimization (CSO): The consortium succeeded in the development, testing and commercialisation of CSO, hereby demonstrating the concept of CSS. Commercially, there are various 'configurations' of the concept implemented as a peer-to-peer solution (p2p - loosely coupled solutions with/without standardization) and in a version where the Commercial Cloud acts as a 'post service' for all communication, called peer-to-cloud-to-peer, or peer-to-common-to-peer. Configurations can freely combine components from the different HEAT partners, where also the individual components or the whole end-to-end solution by Danfoss can be involved. Hereby the flexibility of the overall HEAT 4.0 platform and concepts are demonstrated.
- ✓ Innovation and scientific research: The consortium demonstrated an efficient innovation process from scientific research to commercial implementations. Research results are parallelly developed, tested and finally implemented by the test partners on their IT installations. This was possible due to a high level of trust between the partners and a flexible agreement framework.

Generic findings

Digitalisation was not on the agenda when HEAT 4.0 was started. But the project became one of the driving forces to get the topic into the discussion, strongly supported by developments on privacy, security and increased complexity on the production, distribution sites and the building side (Demand Side Control).

- ✓ HEAT 4.0 demonstrates clearly the value of cooperation, standardisation and common system development that brings Danish partners to the top level of international providers of the best digital DH solutions[4]. However, competitors are learning fast and will challenge the partners in the consortium.
- ✓ Standardization has proven to be valuable for both software providers (REST-API is recommended) and clients (OPC-UA is recommended).
- ✓ Communication between software components has proven an unexpected variety of possible and valuable solutions opportunities.

Individual adoption by partners

- ✓ Improved individual software solutions: All involved commercial partners implemented all relevant components of the HEAT 4.0 concepts in their individual software systems and tools. This included common developments, knowledge sharing, partnering and common business propositions, resulting in improved economical efficiencies and international competitiveness through experience and solutions provided by HEAT 4.0.
- ✓ Adoption of standards and protocols: All involved commercial partners adopted standardized communication protocols and standards to adapt to HEAT 4.0 common concepts, being "HEAT 4.0 Ready".
- ✓ Innovation developed a one-way (sharing data) and a two-way (sharing data and returning forecasts and control sequences) information exchange protocol.

1.2 Findings regarding the Cross System Optimization

- ✓ All three district heating partners (cases) implemented sharing of their data directly and through the cloud component. In all cases, adopted the involved software tools during the project and implemented relevant parts of the CSO concept.
- ✓ All software partners and district heating plants did gain access to their data through standardized interfaces and a two-ways communication (Input: case data; Output: predictions and control time series) structure.
- ✓ All partners did extend the solutions to a fully commercial counterpart during the last year of the project, supporting the fact that the solutions give high value to the operators.
- ✓ Danfoss, parallel to the HEAT 4.0 project, did merge several companies, among these Leanheat. The result is an open and modular End-to-End (e2e) solution 'with similar aspects as the CSO development in the HEAT project'[5]. Hence, the modules from these solutions can be integrated with the HEAT 4.0 components delivered by partners. It can be mentioned that ENFOR is partly owned by Danfoss and that this integration is increased.
- ✓ Leanheat and Neogrid developed 'aggregation services' that aggregate building data for collections of buildings, eventually for subnets and complete district heating nets. This can be utilized in the CSO. Implementation details for the partner cases are summarized in Table 1 to Table 3. PS:[6].

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[4] This was the feedback from a meeting in the IEA DHC Annex TS4 "digitalisation of district heating". Note by the Operator. Also demands from very well-equipped Serbian DH organisation proof the demand for HEAT 4.0 solutions and even more sophisticated solutions.

[5] Cited from the Leanheat Section 6.

[6] At the Hillerød Forsyning case, all staff were changing their jobs during the winter season 2021-22, making evaluation rather difficult.

- ✓ At Brønderslev Forsyning and Hillerød Forsyning all three main components (production, distribution and demand side) are represented, whereas Trefor, Kolding does not produce heat themself but rather buys it, hence not optimizable by HEAT 4.0 in the first run.
- ✓ Data from the district heating systems was provided over the Science Cloud, but will be moved to the 'Commercial Cloud' during the second half of 2022.'
- ✓ The economic findings for the application of CSO are positive for the integration between the production and network. This is also documented by fully commercial applications.
- ✓ There is a high potential effect from temperature optimization in combination with heat loss reduction and efficiency increase at the production units.
- ✓ Temperature optimization by including buildings in the CSO could not be proven and hence remains a hypothetical potential.
- ✓ Extensive utilization of thermal storage capacities supports the potential for replacing gas consumption with flexibility in the district heating networks and buildings. This situation is more pronounced in systems without large thermal storage capacities. On average, the potential for this solution is larger outside Denmark compared to the DH test cases in Denmark applied in the HEAT 4.0 project.

Quantitative results by CSO:

- ✓ Potentials for load shifting by utilising CSO are computed to 2,200 DDK/week (very variable) or 61 DKK/MWh shifted for a Brønderslev Forsyning size DH (see description below).
- ✓ Peak shaving by utilising CSO is computed to 1650 DDK/week (very variable) or 57 DKK/MWh shifted for a Brønderslev Forsyning size DH. This capacity increases a lot in the case where the plant has no thermal storage capacities, which is often the case outside Denmark - 4600 DDK/week (very variable) or 102 DKK/MWh shifted for a Brønderslev Forsyning size DH.
- ✓ Building flexibility, for the district heating system in Brønderslev Forsyning, is computed to be 3825 DDK/year for the building flexibility and 1870 DDK/year for the network flexibility. In a system without heat storage, the gain from flexibility increases significantly. Network flexibility is computed to be 0.775 M DKK/year.
- ✓ Additional value can be hosted from other electricity markets, especially the Intra Day market (definitions of electricity trading markets on e.g. https://www.next-kraftwerke.be/en/knowledge-hub/).
- ✓ The energy saving in buildings is estimated to be 2.8% for the introduction of the building control and an additional 1.7 % after HEAT 4.0 changes (Section 6.3). In some cases, the increased level of comfort "eats up" the savings. The reduction potential in supply temperature is estimated to respectively 4°C for the DH network in Kolding and 6°C for Hillerød. The potential for reduction of the daily peak load for buildings is measured to be 9% on average.
- ✓ From a non-HEAT 4.0 project in Finland, the application of Virtual Heat Storage (flexibility service) in a significant part of the buildings at the Vatajankoski DH system, the energy savings by building control is measured to 12% and peak load reduction did reduce the demand for investments into network expansion.

1.3 Findings regarding the CSO subsystems

Production component (EMD):

- ✓ Communication abilities according to HEAT 4.0 recommendations and standards are implemented in both energyPRO and energyTRADE.
- ✓ A solver is an engine that computes an optimal solution - Solver abilities are improved and modelling of much more complex systems is hereby made possible. This was a requirement by Brønderslev Forsyning and Hillerød
  Forsyning. Higher accuracy was achieved as a result.

- ✓ Modelling abilities are improved dramatically regarding:
  - Hydraulic network modelling, flow, pressure and dynamics relevant for capacity modelling
  - Pumping capacities, cost and limitations
  - Solar energy production, CSP and PV
  - Improved integration with the electrical markets

- ✓ Balance Responsible Parties (BRP) – demonstrated with two independent parties.
- ✓ The testing period at Hillerød Forsyning showed a large fluctuation in weather conditions and energy prices. These conditions were challenging for the two involved alternative control systems, the existing one and the one proposed by EMD. There was however a reduction in demand/production in the EMD control system compared to the existing control system, leading to savings at the production site. No such testing could be carried out at Brønderslev Forsyning.

Network component and forecasting (ENFOR):

- ✓ The supply temperature at all three district heating systems (Trefor in Kolding, Brønderslev Forsyning og Hillerød Forsyning) was reduced. For the selected networks and examined periods, the reductions were 3-5°C at Brønderslev Forsyning, 4-5.5°C at Hillerød Forsyning and 4°C at Trefor, Kolding.
- ✓ The supply temperature optimization did not affect the return temperature adversely in the respective networks.
- ✓ The reduction of supply temperature in the distribution network can bring direct heat cost reductions to the district heating systems.
- ✓ Weather forecasts, heat load forecasts and supply temperature forecasts are very important for production optimization.
- ✓ Quantifiable savings can be achieved at the production site when lowering (/optimizing) the supply temperature at the network.
- ✓ Network flexibility is available and can be activated without any further investments, once HEAT solution software is installed.

Buildings Component Optimization (Leanheat and Neogrid):

Compared to static, linear outdoor temperature compensation, the control algorithms delivered by Leanheat and Neogrid is providing valuable savings.

Because the control targets (comfort conditions) may be changed together with the introduction of control systems, results are difficult to be documented.

Neogrid:

- ✓ As a part of the HEAT 4.0 project, Neogrid rewrote necessary programs to Python codes and an extended back-end is developed for the HEAT 4.0 project, enabling fast prototyping and modelling and optimization in a much more flexible manner than the legacy system.
- ✓ 3rd party access to data is enabled with authentication and authorisation mechanisms.
- ✓ Online control and condition monitoring are developed e.g. regular performance reporting.
- ✓ Improved online controls were demonstrated:
    - New semi-automatic optimised adaptive heat-curve concept at building and aggregated building levels.
    - Peak reducing control for an aggregate of buildings.
    - Reduction of contribution to evening peak via optimised control for an institutional building.
    - Reduction of return temperature via optimised control in low-energy single-family houses.

Leanheat:

Due to the merger with Danfoss, the Leanheat building software is integrated with the whole software package of the Leanheat Building component (see above about the whole e2e suite).

An existing control system without sensors (no temperature sensors in the building) is expanded to be able to achieve energy savings for the individual building and similar services are expected for the DH net (peak shaving, virtual energy storage etc.)

The energy efficiency software is improved to cover district heating optimized control, peak shaving in the DH system and in the electricity systems (demand response).

The implementation of Leanheat controllers in Trefor, Kolding showed a reduction of 9.7% and + 2.4% with an average -2.8% (60MWh) in 2020-2021 and -4.2% (131MWh) in 2021-2022. The corresponding case at Hillerød Forsyning showed savings of 25% and -2% in the individual buildings, with an average for all involved buildings of 8% (101MWh) in 2020-2021 and 10.5% (202 MWh) in 2021-2022, respectively. Savings in individual buildings seem to be less and fluctuate more. The case in Brønderslev did not include enough buildings to make a statement on these collected data. Variations can be attributed partially to user behaviour and their increased user comfort demand.

Leanheat observed the demand for an aggregated representation of buildings (not the individual buildings themselves). In this way, a CSO methodology can be improved a lot. The solution is called Virtual Heat Storage (VHS) and is demonstrated at additional DH systems in Vatajankoski (Finland) where the end-to-end solution by Danfoss Leanheat is demonstrated. In this case, the aggregation solution showed a 13% decrease in heat consumption by the 13,000 inheritance.

Buildings that integrate with the CSO concept demand rather advanced control systems and communication abilities. The recruitment of such buildings is a critical challenge and may be solved by two different strategies:

a) Moving control for indoor services to the district heating (direct control, leasing, price control etc.)

b) Applying CSO for networks with high adoption of adaptive control in buildings that are able to communicate with their surroundings.

While a) is not the normal operation for Danish DH operators, still it may be a relevant opportunity for export. b) seems unrealistic as a business case in the near future, especially in Denmark.

In future, the recruiting of buildings ought to be focused to recruit building operators that have a high share of buildings in a given network or subnetwork. In this case, a business model would combine the investment in the building operation with the receiver of savings. Also, the procedure of recruiting buildings must be made extremely efficient and motivated by the district heating operator through their business considerations.

In a commercial setup, the ratio of efforts required to get into a building (man-hours and installation costs) over the return on investment (impact on the system operation, energy saved, income generated by the installation, …) is not supported.

Precondition findings:

- ✓ Data were collected during long periods of the project's lifetime.
- ✓ Control operation of district heating is a very important issue for the operators and has a large economic impact.
- ✓ Operators in charge of controlling DH systems are experienced and professional people and the introduction of new technologies is not necessarily received with open arms.
- ✓ Due to a lack of control over a complex system such as district heating, data is applied in the above studies over short periods, instead of annual values.
- ✓ The CSO idea was designed to include the entire system from production to distribution to buildings. Despite very large efforts to recruit building owners to participate, none of the three DH systems (cases) was able to find a critical mass of buildings to make an impact on e.g. heat losses in the district heating network.

General HEAT 4.0 findings:

Ideally, experiments are designed to isolate a single effect on the investigated system. In our case, the system consists of the whole district heating system. In this case, the isolation of one single effect, like the impact from the CSO or HEAT 4.0 in general, is not possible, because it is difficult to measure all changes that are continuously made within the DH system. This must be taken into consideration when evaluating the impact of the CSO on the performance of the whole DH system – or of its main components (demand, distribution and production).

HEAT 4.0 has proven to be a relevant business solution, having various fully commercial implementations. The role of an integrator as a single point of contact for the DH operator seems essential. There is a demand for developing a specific business model because company investments are not correlated to savings in the three involved organisations.

TERMIS simulation of heat losses in pipes on a detailed dynamic pipe network model has been applied to the case at Brønderslev Forsyning.

2. Introduction

The HEAT 4.0 project started with a long list of possible ideas to improve district heating through digitalisation. One of the most important in this list of innovations is the application of 'Cross System Optimization', introduced in this section.

The designation Cross System Service (CSS) is introduced by HEAT 4.0. CSS can be any digital or digitally supported solution that combines 'across' independent aspects of the common system. The idea is to combine the individual aspects/components/software to deliver a service across the whole system, hereby enabling improvements to the whole system. This system architecture consists of 'holistic' services, like the CSS.

Concerning district heating systems two main dimensions are targeted within the project[7]:

- the 'component' dimension is defined across the production, distribution in the pipe network and the demand side.
- the 'temporal' dimension is defined across the operation, short-term and long-term planning, informing the digital models involved by generic findings at each level.

The largest effort was made on the component dimension (a) and the current report presents the findings from this work. The temporal dimension (b) is addressed by DTU Compute and DTU Management in research projects, reported in scientific papers under the keywords: 'Hierarchical optimization of production and network operation' and 'Frigg'.

In the following, we will focus on the optimization across the component dimension of the district heating system.

2.1 Cross System Optimization (CSO) – the concept

Cross System Optimization (CSO) is a variation of the generic CSS concept. The target is to optimize the district heating system across the whole system. There can be different targets for such optimizations in general, but also concerning the CSO. One possible objective can be the optimization of the supply temperature that determines the heat losses in the net (to be minimized), or the sum of energy used for the production or the amount of heat delivered or many other targets.

Again, this could be done across different dimensions, but in the work presented here, a service that optimizes across the three main components as shown in *Figure 1*, including Production (PO), distribution in the district heating Network (NO) and demand from typical Buildings (BO)[8].

[7] A third dimension could be added by the concept of waste heat and sector coupling. In this case, the bridge is 'across' the independent utility systems, nets and industrial systems.

[8] In more advanced implementations, other components such as waste heat, prosumers (customers in the DH that is consuming and producing heat/cool energy themselves) and others could be added to the overall system optimization.

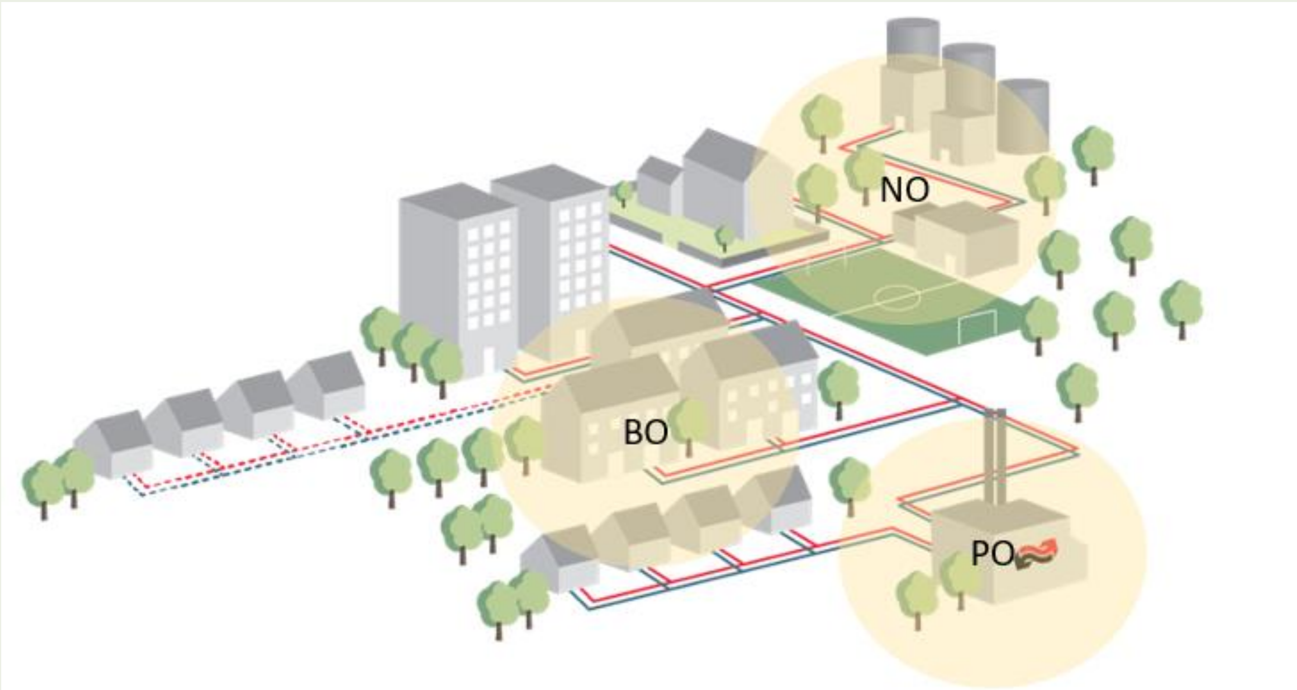

Figure 1: The holistic District Heating system model by HEAT 4.0, composed of production, distribution and demand.

The CSO concept can be implemented in various ways, involving various numbers and combinations of components that we will call configurations. There are two main configurations addressed by the project:

1. Peer to Peer (p2p)
2. Peer to 'Cloud' to Peer (p2c2p)

The 'Cloud' is a data-sharing component. In future solutions further 'common component' can be imagined, hence the 'c' can also stand for 'Common Components', hence the configuration can be called 'Peer to Common Component to Peer'.

Before HEAT 4.0, any software would have to find a communication methodology with other 'component' software, resulting in a situation as sketched in *Figure 2*.

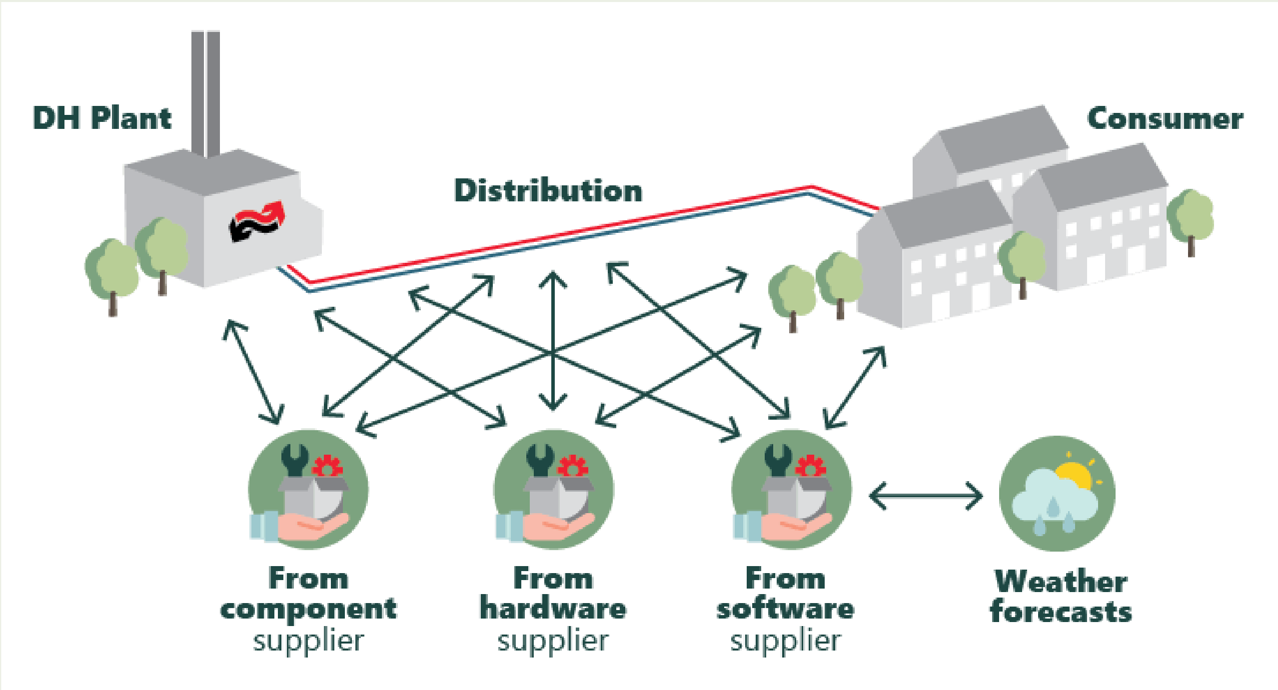

Figure 2: Implementation of individual software packages end in a digital 'spaghetti' architecture.

From a district heating operator's view, the situation drawn in Figure 2 is relatively simple to implement for each software package, but it is hard to maintain when many software tools from various providers are applied. HEAT 4.0 addresses this challenge, among many others.

In the peer-to-peer (p2p) solution for the CSO, each optimization software component communicates with all others that are relevant for the purpose, resembling the 'spaghetti' architecture above. HEAT 4.0 solves this challenge in a few steps.

As a first step, HEAT 4.0 adopts several ICT standards, whereas the Industry 4.0 protocol OPC-UA is recommended for the communication from hardware and the SCADA infrastructure of the DH operators to the software components and vice-versa. This recommendation is strongly supported by the general development of the software and control industries that support this protocol in almost any hardware or control system – SCADA for example that is applied by the DH operators as a central control unit for most of the DH systems. For IoT devices, more than one protocol has to be supported, because a common standard does not exist (yet). For communication between software systems, the REST-API approach is recommended. All these recommendations were developed, tested and reported below.

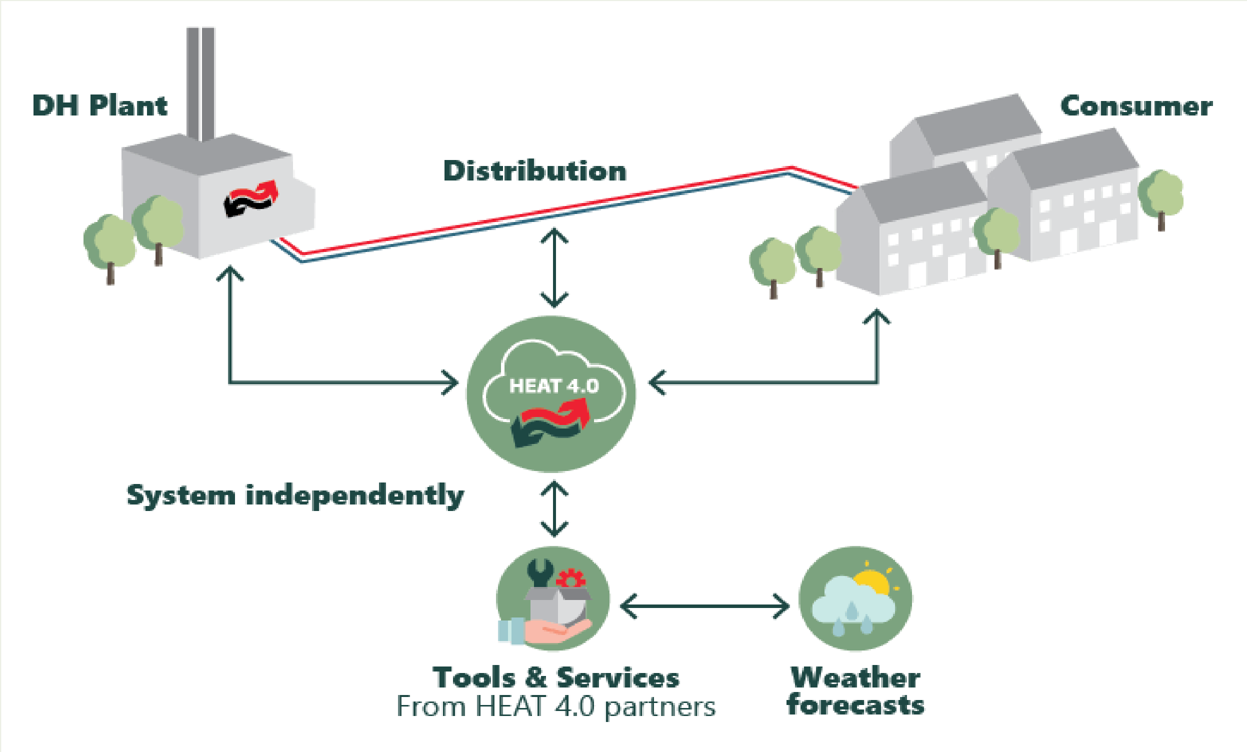

Figure 3: Introduction of standards and protocols and a common HEAT 4.0 platform into the DH infrastructure.

Figure 3 shows how the introduction of standards impacts the overall system IT architecture, introducing common HEAT 4.0 components, especially the 'Common Cloud' for data management and sharing. The 'Cloud' is a common data-sharing component.

HEAT 4.0 recommends standardization in the following communication solutions:

- Communication from DH operator's SCADA infrastructure to the software components.
- Communication of predictions and control values from the software components to the DH operator.
- Communication between the software components.

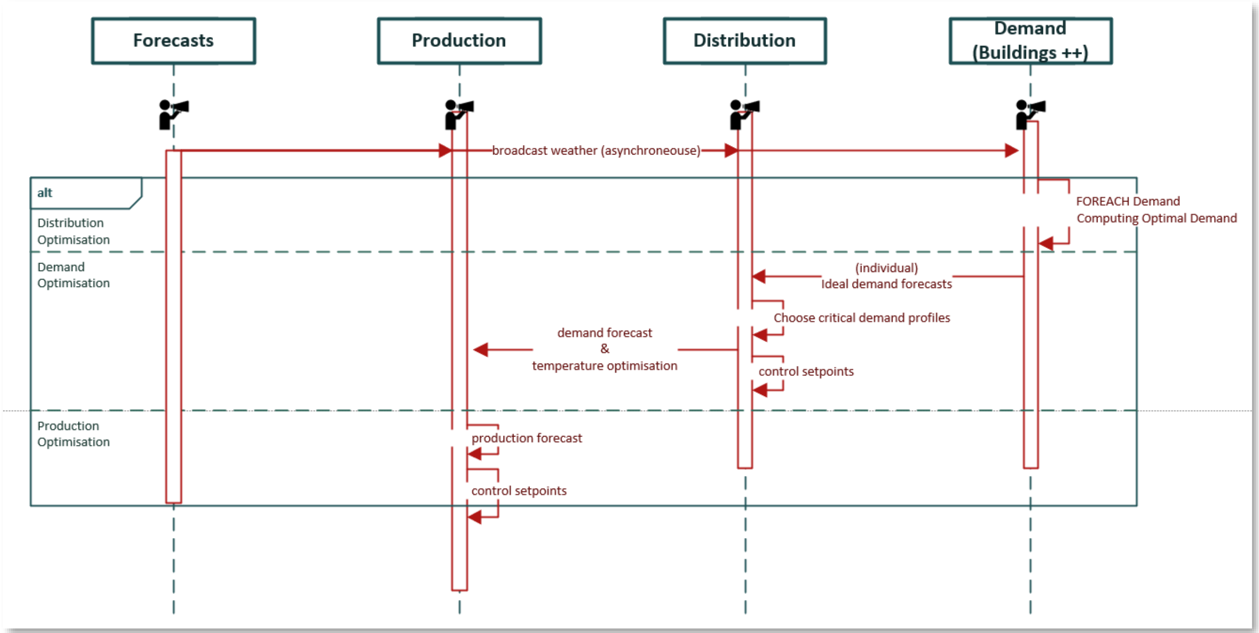

Figure 4: CSO p2p in a broadcast implementation (one-way protocol[9]) where anybody can grab the relevant data from others.

Any configuration of the CSO depends on the communication of shared data. Hence, every software has to be able to receive and deliver data according to HEAT 4.0 specifications. Such data are in general time series of numerical forecasts and control values. In the current project we agreed on a time horizon of 7 days and hourly values, hence a vector of 168 values for each aspect of the overall optimization. This can be weather parameter forecasts, load forecasts, production forecasts and many others. The communication is recommended to be in OPC-UA for the plants and installations - and REST-API for the software communication.

The CSO implements methodologies that go across the individual software solutions. The most important of this kind is the data-driven mathematical modelling for forecasting and optimization that delivers the models for the involved aspects and components. This topic is implicitly impacting the value of the CSO but is not described in this section. Interested readers can find more information on this subject at the project homepage at https://heatman.dk or the CITIES homepage, https://smart-cities-center.org. Below, the individual descriptions will however mention some details on their implementation that may involve such methodologies. It is not the ambition of this current report to completely document the relations between methodologies and implementation and their impact on the CSO.

In the next section, the implementation cases are described. These are applied to install all involved components and concepts for development testing and collection of documentation purposes.

2.2 Case descriptions

Three district heating partners joined the consortium – Brønderslev Forsyning, Hillerød Forsyning, and Trefor in Kolding to enable the implementation, innovation, testing, and collection of results for the HEAT 4.0 solutions. Full-scale implementations of the HEAT 4.0 solutions were necessary to gain insights to improve the innovations during the project lifecycle. The below results are a collection of these insights.

[9] Please note that two-ways communication can be done in the same way, but a negotiation between components cannot be efficiently facilitated by these means.

The collection of results was carried out in three major steps:

1. Collection of data before any impact by the HEAT 4.0 project. (Baseline)
2. Installation of the software from relevant partner organisations.
3. Continuously improved individual software packages, common communication and common improvements. (The result was collected along during period.)

Further, a common infrastructure component for data sharing has been developed. For development purposes, the Science Cloud for CITIES was used. The plan was that a Commercial Cloud would be ready for the last evaluation in the winter season 2021-22. However, this was not the case and hence evaluation is made on basis of the application of the Science Cloud by CITIES. Information on the Commercial Cloud will be available together with this report on the HEAT 4.0 homepage (heatman.dk).

Figure 5: District heating systems considered in CSO (original project demonstration cases are painted orange, new developments subsequently this project are painted purple).

The three district heating partner cases are all placed in Denmark and geographically spread from north to south. See *Figure 5* and also have a variety of characteristics as described in this section.

Brønderslev Forsyning, placed in the northern part of the Danish mainland, Jutland, has a very complex DH production setup, involving a biomass plant, an Organic Ranking Cycle (ORC) co-production unit, concentrating solar collectors, central heat pumps, gas- and electric boilers and an 8,000 m^3 thermal storage tank. The distribution net consists of 3 subnets. The town has 12,600 citizens, where 4,800 citizens are DH customers, mostly residential buildings, public buildings, some industrial, and commercial buildings and all that such a town needs.

Hillerød Forsyning, located north of Copenhagen, is delivering DH to a growing population in the city and a growing industry. This district heating is running with a traditional co-generation plant that has to be phased out in 2023 due to a special agreement that is running out at this time. This change is demanding a drastic adjustment in heat production. 95% of all heating is delivered by this system, cooling is added during the HEAT 4.0 lifecycle and adds to the production opportunities. The production site consists of 52% biomass, 44% gas, 3% waste heat, and 1% central solar heating. The system consists of an old central power plant that is prioritised to run all the time, and a small solar thermal plant, that delivers a large share of the heating demand. The network consists of various sub-nets.

TREFOR in Kolding at the southern part of the mainland, Jutland, buys the heat from the regional company, EWII and distributes the heat through 17 subnets to the 62,000 inhabitants with a rather large industrial sector, residential, public, industrial and commercial buildings. Since Trefor is a multi-utility company, the IT infrastructure is driven by a common section that defines the rules for the heating sector. Hence the framework for HEAT 4.0 was strongly influenced by this organisation.

Commercial cases: The CSO is implemented under commercial conditions at Assens Fjernvarme (Fynen) and Sindal Fjernvarme – both situated in Denmark. These two cases prove the interest in the concept. Also on the international plan, HEAT 4.0 efforts are ongoing. Insights from these cases are not collected and reported here. Anyway, one finding from the international investigation is, that many places do not have the rather large thermal storage tanks that Danish DH systems have. This impacts the results of introducing HEAT 4.0 a lot. Systems with no or small thermal storage capacities can take even more advantage of the HEAT 4.0 solutions compared to the Danish, as shown in the results below.

About configurations: CSO builds on individual software components, delivered by the involved HEAT software developers, shown in the below figures and tables.

Table 1: Digitalization aspects of CSO for individual partner organization. The number under the plant organization shows the number of test-subnets of the district heating network and in parenthesis the number of installations on all possible subnets.

Implementation Cases					Brønderslev Forsyning	Trefor	Hillerød Forsyning
Companies		**Prediction**	**Communi-cation**	**Installa-tions**			
EMD	EnergyPro EnergyTrade*			PC	X		X
ENFOR	HeatSolutions: • MetFor* • HeatFor* • HeatTO*	- Locally optimized weather forecast - Heat load forecast - Optimized supply temperature	Many options: -text files (CSV), -ftp, sftp -database access -REST-API (web service)	On site / Cloud	Whole system (3 of 3)	Whole system (15 of 15)	Whole system (7 of 7)
Neogrid	PreHEAT	-Minimum supply temp. -Return temp. -Energy demand	REST-API (CSV)	Self-hosted cloud infrastructure			
Leanheat/ Danfoss	Danfoss Leanheat software suite: • Leanheat Building • Leanheat Network • Leanheat Monitoring • Leanheat Production • Virtual Heat Storage (VHS) service		REST-API (JSON) (REST-API (CSV)) REST-API for VHS	On site Cloud			
DESMI Kingspan/ Logstor	No final solution		REST-API (CSV)				

** Self-learning data-driven, self-calibrating models (grey-box models, Machine learning[10]).*

[10] The Leanheat solution was in early days adopting Artificial Intelligence, self-learning non-parametric models, but changed to 'parametric' greybox models in term of HEAT 4.0.

Table 2: Data communication interfaces between HEAT 4.0 project partner software. (X) means possible interface.

Communication and connections	EMD	ENFOR	Neogrid	Leanheat/Danfoss (e2e)	DESMI	Logstor Kingspan	CDK (Commercial Cloud)	DTU (Science Cloud)	Plant directly	Balancing Responsible Parties
EMD		X	X	X	(X)		X	X	(X)	X
ENFOR	X		X	X	(X)		X	X	X	
Neogrid	(X)	X		X			X	X	(X)	
Danfoss Lean-heat	(X)	X	X		X	(X)	X	X	X	
DESMI							X	X	X	
Kingspan Logstor										

Table 3: Installation survey for the three HEAT 4.0 partner district heating cases.

	EMD	ENFOR	Leanheat	Neogrid
Brønderslev Forsyning	EnergyPro EnergyTRADE (installation not in use)	HeatSolutions: MetFor HeatFor HeatTO		- 2 single family house (BR2020) - 1 kindergarten - 1 office + workshop
Hillerød Forsyning	EnergyTRADE (installation not in use)	HeatSolutions: MetFor HeatFor HeatTO	Sensorless installation 12 multi-family buildings (~500 apartments)	- 1-2 single family house - shopping mall - conference centre
Trefor Kolding		HeatSolutions: MetFor HeatFor HeatTO	Full Leanheat installation 13 multi-family buildings (~400 apartments)	

3. Production Optimization Solution by EMD

This chapter describes EMD activities in the HEAT 4.0 project connected to the production optimization solution provided by EMD. It describes improvements to the software suit developed by EMD – energyPRO and energyTRADE, as well as changes needed for integration with the systems of the HEAT 4.0 partners.

3.1 Software suite for production optimization

The production optimization solution provided by EMD consists of two main software tools – energyPRO and energyTRADE. Both tools are well-recognized tools in the Danish market.

energyPRO is used for detailed technical and financial analysis of both existing and new energy projects in a very user-friendly interface providing the user with a clear overview of the project. The software offers a long range of technical and economic reports including a graphical presentation of the simulated operation which provides an overview and in-depth understanding of the dynamics of a complex energy system.

energyTRADE intelligently optimizes the planning of simultaneous bidding in a day-ahead schedule, regulating and primary reserve electricity markets. Based on various input data e.g. weather forecasts, electricity spot price prognoses, expected heat demand, and thermal storage content, energyTRADE calculates the optimal operation quarterly, half-hourly, or hourly time steps. The output is a detailed graphical and numeric production plan containing the proposed operation for each energy unit. The production plan shows the amounts of energy and bidding prices to be offered in every time step and the estimated economic result for the specified period. The production plans with bidding prices and quantities as well as actual production schedules subsequently received are seamlessly exchanged between the energy plant and the Balance Responsible Party (BRP) directly in energyTRADE. A derived benefit of having an energyTRADE solution is that it also includes a detailed energyPRO model setup of the energy plant, which can be used to analyse any changes in the plant operation strategy or investments in new technology.

3.2 Improvements to the production optimization solution

To be able to satisfy the requirements of the plants and the HEAT project, improvements to the software suit were needed. These were realized during the HEAT 4.0 project.

3.3 Implementation of a MILP Solver

To be able to find optimal operation of very complex systems as it is seen in the participating plants in Brønderslev Forsyning and Hillerød Forsyning, as well as other plants where the HEAT 4.0 concept was used, a new optimization method was introduced in the EMD software. A Mixed Integer Linear Programming (MILP) solver was implemented. The MILP Solver finds the solution to a problem defined with linear constraints and objective function, where some of the variables can be binary or integer. The ability to describe an energy system with a set of linear constraints enables to use a MILP Solver as a calculation method in energyPRO.

This implementation allowed optimizing the operation of highly complex systems where:

- units are producing various energy outputs (e.g., heat, electricity and cooling)
- the operation of some of the units depends on the operation of others (e.g., heat recovery, Organic Rankine Cycle (ORC) running on heat produced from CSP)
- units with complex efficiency curves
- units operating with restricted fuel consumption

3.3.1 Development of a CSP model

EMD developed a mathematical model of Concentrated Solar Power (CSP) units, which will be able to accurately estimate the thermal power output from the CSP installed at Brønderslev Forsyning based on the prognosis of solar irradiance provided by ENFOR. The model was validated against SAM, a state-of-art model of this technology, and will be validated against the real SCADA data measurements from Brønderslev Forsyning. The validation against SAM[11] proved to give goods result for a test scenario:

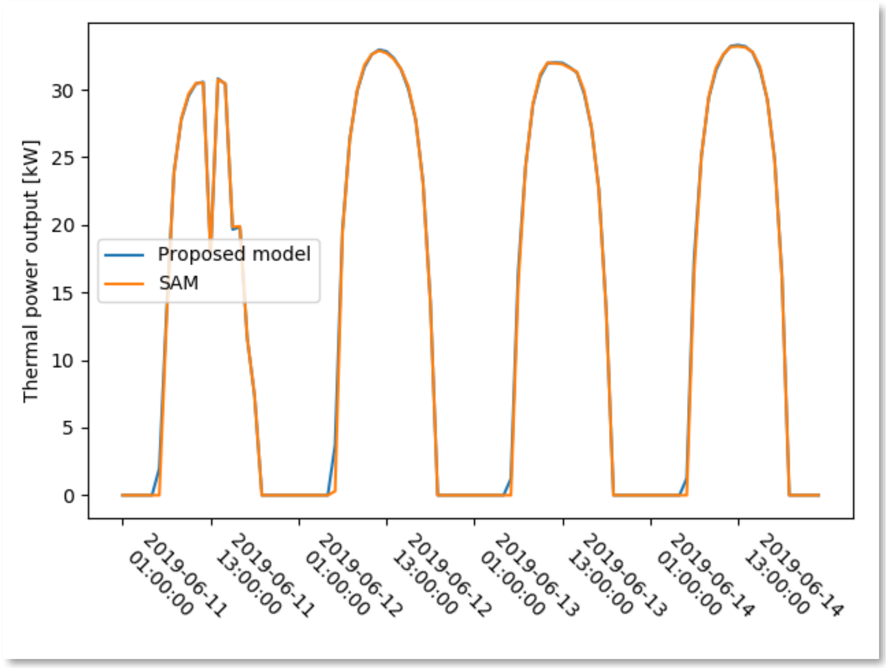

Figure 6: Validation of CSP model against SAM model, thermal power production calculated with both models plotted for four days in June 2019. The models align very well, hence the performance of the proposed model is acceptable.

This development will be a valuable point in the future for renewable district heating systems, where the heat production from CSP may play an important role. Accurate estimations of heat production will play a vital role in short-term production optimization.

3.3.2 Hydraulic calculations for heat transmissions

The hydraulic calculation implemented in energyPRO and energyTRADE can be used in systems with multiple district heating sites such as Brønderslev Forsyning and Hillerød Forsyning. It allows the inclusion of constraints, that the DH network may cause. It thus allows you to include in the economic optimal investments besides production units and storages - also the network, considering the diameters of the pipelines, the value of high insulation, and low pipe roughness. Pumping cost is also included. Finally, the temperatures of supply and return can be included in the calculation of the maximum possible transmission capacity. This allows for a more accurate calculation of optimal production, where the transmission capacity limits are calculated for the expected conditions allowing for operation optimization of peak boilers or flexibility of buildings and networks in the system.

[11] System Advisor Model Version 2020.2.29 (SAM 2020.11.29). National Renewable Energy Laboratory. Golden, CO. Accessed December 27, 2020. https://sam.nrel.gov

The user can specify inputs regarding transmissions as shown in *Figure 7*. Together with the specification of operating temperatures in each of the regions, the inputs allow for the calculation of maximum transmission capacity. The transmission capacity can be variable if operating temperatures are specified as time series.

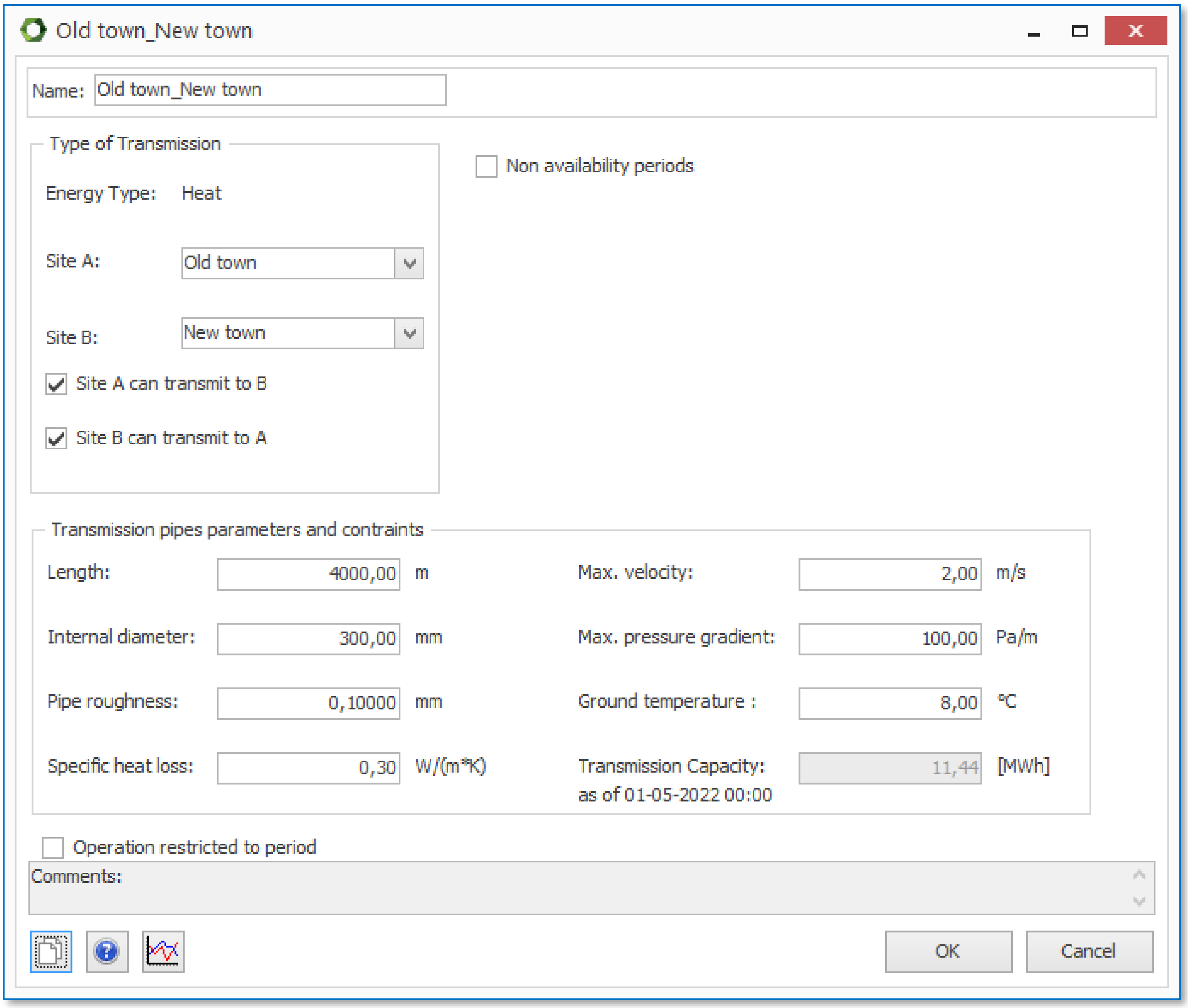

Figure 7: Setup of transmission line with new hydraulic model in energyPRO.

After the calculation is performed the user can see the hydraulic parameters of the transmission grid, as presented in *Figure 8*.

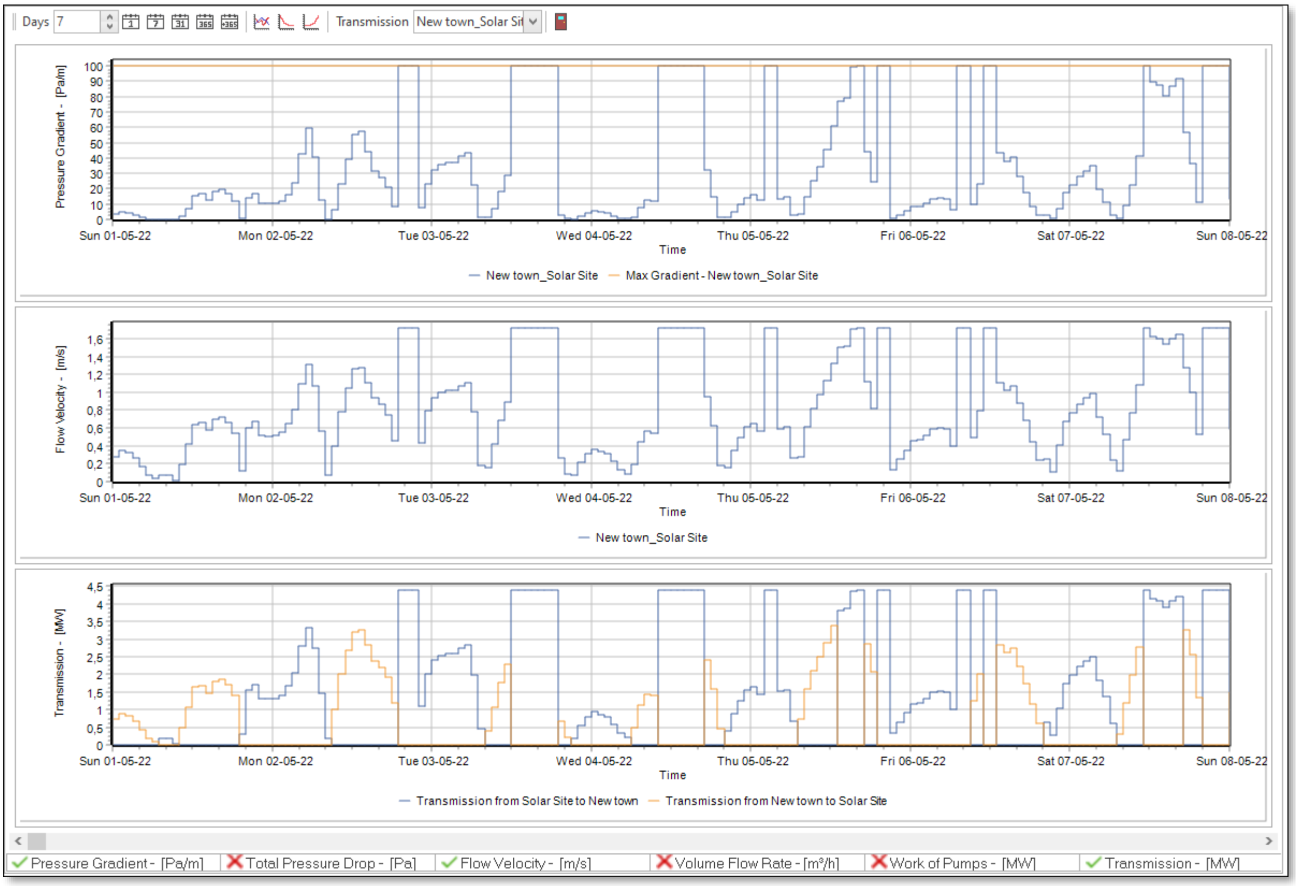

Figure 8: Flow parameters in a transmission line are calculated in energyPRO. Pressure gradient [Pa/m], flow velocity [m/s] and transmitted energy [MW] for each timestep in a week of operation.

3.3.3 Improvements to PV model for Assens District Heating

Improvements to PV model present in energyPRO were made to accurately calculate the expected production from PV panels in energyTRADE. This was done based on SCADA measurements provided by Assens Fjernvarme, where differences between predicted production and realized production were found. The losses coefficient was tuned and the prognosis input data were re-analysed and corrected to reflect the correct timesteps to be used. Assens Fjernvarme was an interesting case, since the installed PV panels are facing east and west, rather than the usual south orientation.

3.4 Communication with other tools

An important part of work in HEAT 4.0 was to establish communication with tools provided by other partners in the project. This is important in the real-time optimization tool energyTRADE, which needs input from SCADA system, the prognosis of weather conditions and demand, the prognosis of day-ahead electricity prices, and communication with balance responsible party.

3.4.1 ENFOR prognosis

EMD receives from ENFOR prognosis for the coming 7 days for:

- Heat demand
- Temperature
- Irradiance

• Wind speed

The prognosis is delivered via FTP[12] server from which EMD reads the data. A dedicated 'data provider' was created in energyTRADE, which will work with any ENFOR FTP server with a similar structure. The data is updated every hour and is read into energyTRADE to be used in production optimization. An example of the prognosis is shown in *Figure 9*.

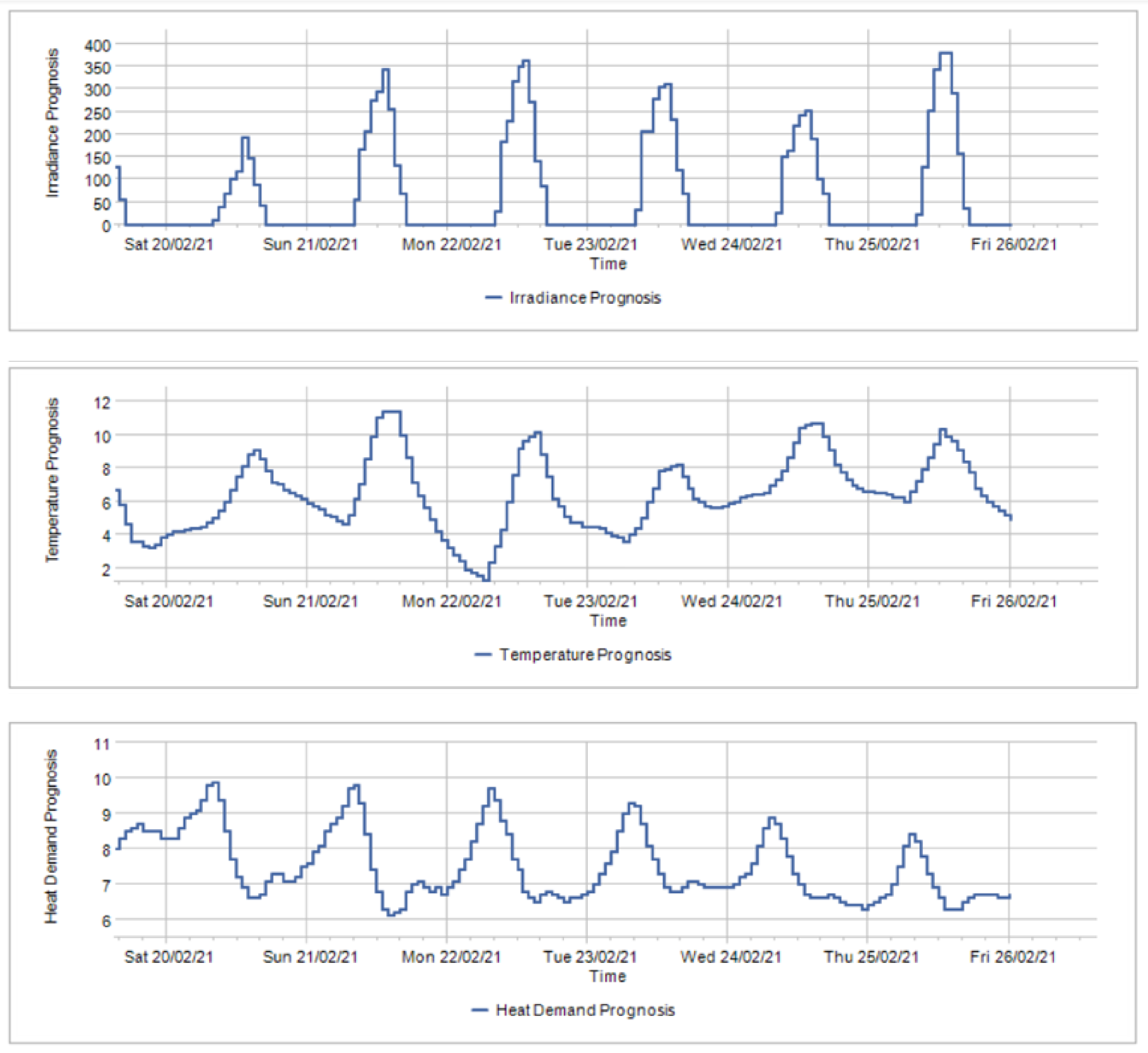

Figure 9: Prognosis for irradiance [W/m2], temperature [°C,] and heat demand [MW] provided by ENFOR and used in optimization in energyTRADE. Example of one week of prognosis in January 2021.

[12] The ftp protocol is applicable in this case where no critical data such as weather data is transferred. For critical control data and privacy-related data, this protocol is not recommended by HEAT 4.0.

3.4.2 SCADA system measurements

As mentioned in the introductory sections above, data communication is redirected through a common cloud component. At the beginning of the project, the 'Science Cloud' was delivered as a research component by the partner DTU. Communication is enabled through a REST-API interface. This approach enabled the DH operators to provide their data to the Science Cloud and from there to the partners. For the three HEAT 4.0 demonstration sites, this approach was applied.

EMD created a dedicated reader to collect the data and use it in energyTRADE. This allows to account for heat storage level in the optimization and displaying the historical operation of the system.

3.4.3 Communication with balanced responsible parties

Through energyTrade, DH operators can trade electricity demand and production to the energy markets. Two such trading paths were investigated in HEAT 4.0 where the following trading companies were involved:

Energi Danmark

Energi Danmark is the balance responsible party (BRP) in Brønderslev. EMD has access to the API provided by Energi Danmark, where data about planned production of the traded plants are presented. This means the hours and amounts when specific plants won production/consumption on the spot market or won upward/downward regulation.

The API is lacking the possibility for energyTRADE to send bids to Energi Danmark.

The URL to the API: https://pba.energidanmark.dk/ExternalServiceLibrary/PBAProducerService.svc

Danske Commodities

Danske Commodities is the balance responsible party in Hillerød. EMD has access to the API provided by Danske Commodities, where the data about planned production of the traded plants are presented. This means the hours and amounts when the specific plants won production on the spot market or won upward/downward regulation.

EMD can send bids to Danske Commodities. This means we have two-way communication with the market.

The URL to the API: https://api.pba.dcgeneration.com/api

Documentation of the API, with the description of what should be a call to get the desired response:
https://api.pbatest.dcgeneration.com/swagger/ui/index#/ResultsApi

3.5 Implementation of production optimization in HEAT 4.0

Within the HEAT 4.0 project, EMD did implement the production optimization for two of the three DH partners, Hillerød Forsyning and Brønderslev Forsyning, involving different market actors. Trefor buys its heat from EWII, a sister organisation of the overall utility construction in Kolding. In the current section, these two implementations are explained.

3.5.1 Installation and development of energyTRADE at Hillerød Forsyning

An energyPRO model was developed to represent the real district heating system at Hillerød Forsyning. The graphical representation is shown in *Figure 10*.

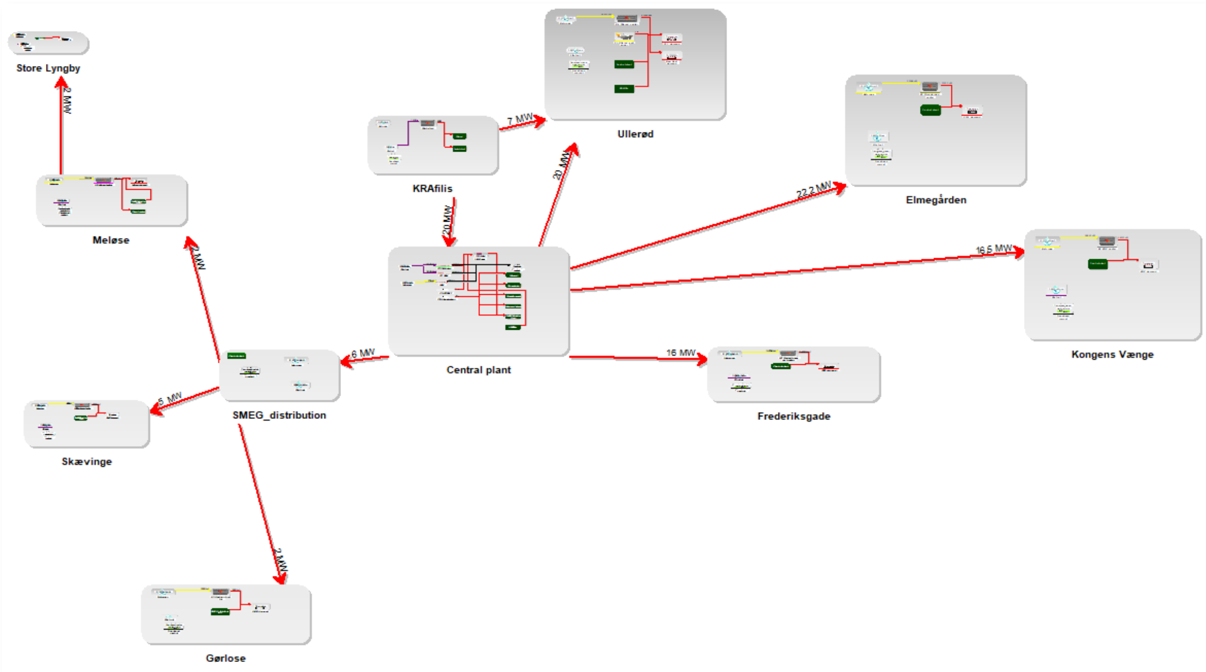

Figure 10: Model of Hillerød district heating used in energyTRADE.

The district heating model in Hillerød was developed in close collaboration with Hillerød Forsyning and was validated with their operation. It includes models of all production units, demands, and transmissions in the system.

Based on this model, the energyTRADE model was created. In it, the communication with other systems was established, as described in the previous section. The model includes, among others:

- Automatic update of daily gas prices – a very useful feature considering the highly variable gas prices
- Readings from the SCADA system for a new unit introduced to district heating system in Hillerød
- ENFOR prognosis fetched from ENFOR's FTP
- Connection with Hillerød Forsyning's balance responsible party – Danske Commodities

The improved model has been installed locally in the DH system in Hillerød and is available for the plant operators, a screenshot from the system shown in *Figure 11*. The results are explained below.

Figure 11: energyTRADE installed locally at Hillerød Forsyning.

3.5.2 Installation and development of energyTRADE at Brønderslev Forsyning

An energyPRO model was developed to represent the real DH system in Brønderslev Forsyning. The graphical representation is shown *Figure 12*.

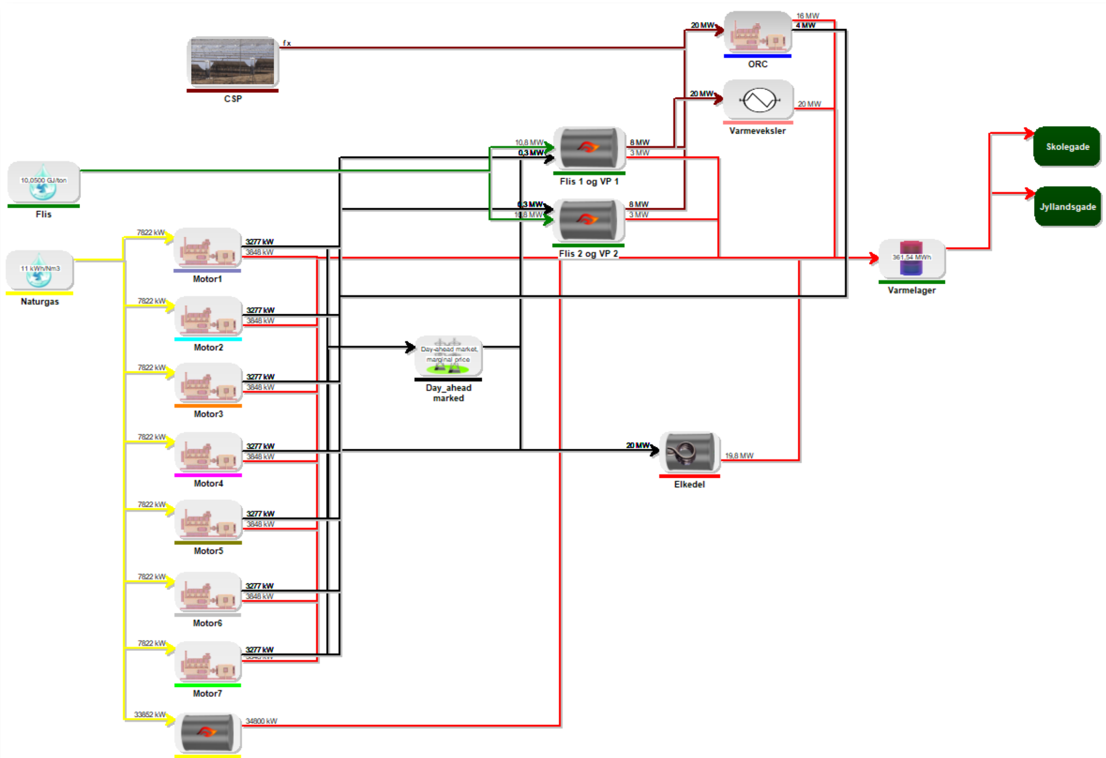

Figure 12: Model of Brønderslev Forsyning district heating used in energyTRADE.

The model was developed in close collaboration with Brønderslev Forsyning. It includes models of all production units, demands, and transmissions in the system.

Based on the energyPRO model, the energyTRADE model was created. In this, communication with other systems was established, as described in the previous section. The model includes, among others:

- Finalized connection to ENFOR to fetch demand prognosis for all areas in Brønderslev Forsyning
- Working reading of SCADA measurements from the Brønderslev DH system
- Connection with Brønderslev Forsyning's balance responsible party – Energi Danmark
- Automatic update of daily gas prices – a very useful feature considering the highly variable gas prices

On top of the above-mentioned improvements, a new functionality was introduced in energyTRADE for the calculation of heat production prognosis from the CSP. The prognosis is calculated based on the new CSP model developed in 2020. It is done on EMDs server and the resulting heat production prognosis is read into energyTRADE. This new workflow, developed for Brønderslev Forsyning, will contribute to the higher applicability of energyTRADE. It will allow for faster implementation of new physical models, which can now be written in Python and used in energyTRADE easily.

The improvements and development resulted in a well-functioning energyTRADE model of Brønderslev DH system. The result of optimization is presented in *Figure 13*.

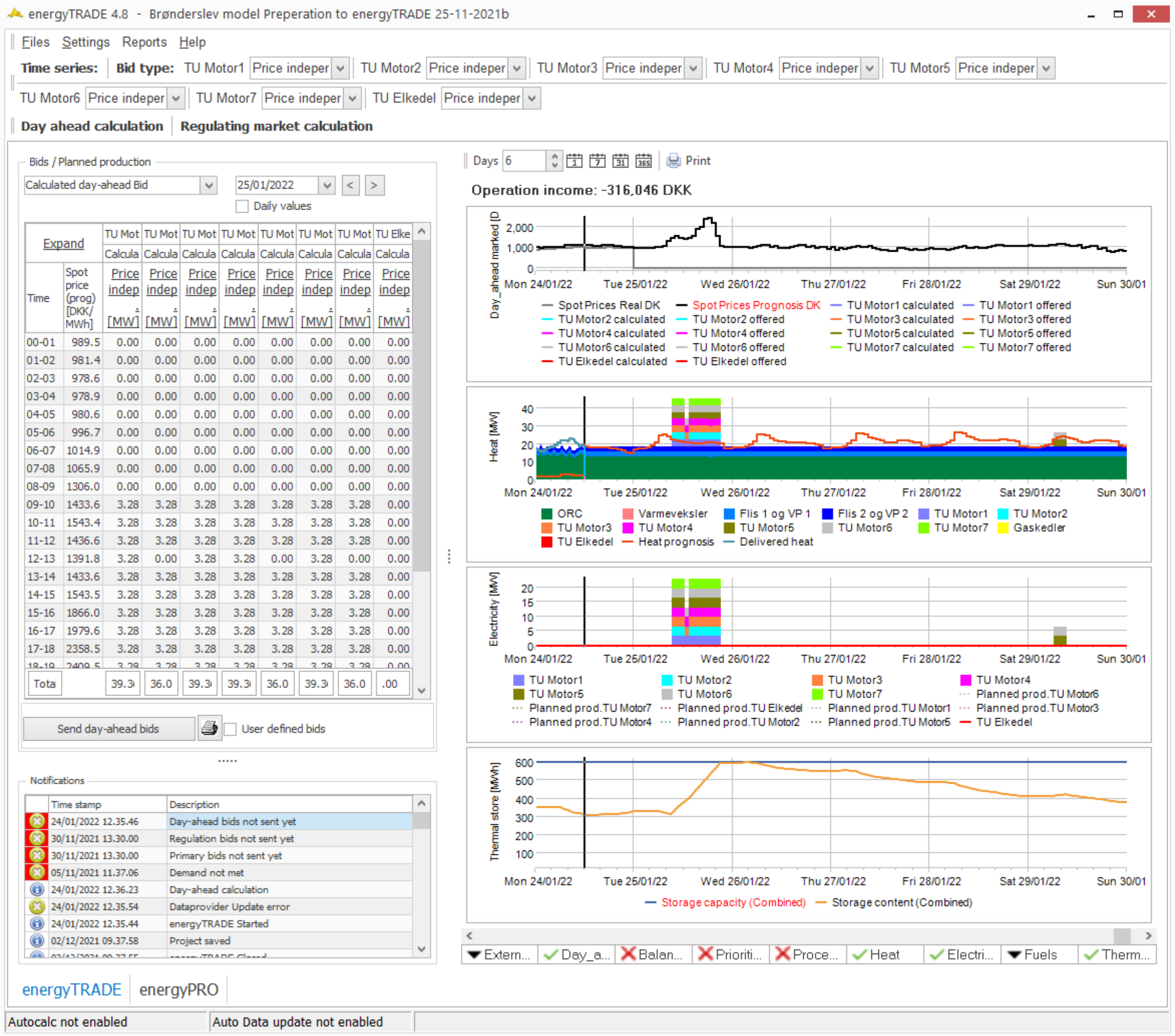

Figure 13: energyTRADE optimization of Brønderslev district heating. A screenshot of energyTRADE's graphical user interface with a calculation performed for one week in January. The optimal operation of the units, hour by hour, is shown in the graph. Bids suggested for the gas engines are summarized in the table on the left.

3.6 Lessons learned from the real implementation of CSO by EMD

The Cross-System Optimization was tested at Hillerød Forsyning for a week of operation. It was done in parallel with the existing operating system between 7/03/2022-13/03/2022.

The general points from the plant operator:

- The testing week was a week with high variability in heat demand.
  During peak hours the consumption was 80-90MW/h, when the sun started shining, it went down to about 40MW/h.
- There was high variability in gas prices.
  The day ahead price was 216€/MWh, 2 days later it went down to 130€/MWh.
- Adjustments of the model are needed to avoid short periods of operation (3-4h) and changes in operation state during the night (start or stop).

- There is a high need to have the functionality of calculating regulating bids, especially due to the highly variable prices in the gas and electricity market. In energyTRADE the prices are registered to be available.
- Neither the currently applied prediction nor the prediction provided by ENFOR, could predict the changing conditions accurately. In the energyTRADE results shown below the ENFOR predictions are included.

The planned production generated on 07-03-2022 from the existing tool (Mentor planner) at Hillerød Forsyning and energyTRADE are shown in *Figure 14* and *Figure 15*, respectively. The generated plans differ, the Mentor planner suggests operating the HKV unit during more hours, compared with energyTrade.

The advantage of CSO cannot be found directly by comparing the two suggested operations. The production optimization using energyTRADE suggests operation in hours with higher electricity prices. However, due to the differences in demand prognosis, the gain cannot be directly quantified.

It is clear from both suggested production plans, that the storage is extensively used when the gas turbine (HKV) is in operation. This could suggest a potential for full CSO, where the flexibility of network and buildings is incorporated into the model. This flexibility could be used to increase earnings from electricity sales when high prices are expected in the market.

All in all, the real implementation of the DH system at Hillerød Forsyning proves that the improvements introduced to energyTRADE during the HEAT 4.0 project result in a good product for our customers. With the new functionalities, EMD will be able to offer the product to more district heating plants. Today, EMD already sees an increased interest in energyTRADE and is satisfied to be able to offer a product, which suits the needs of the DH companies.

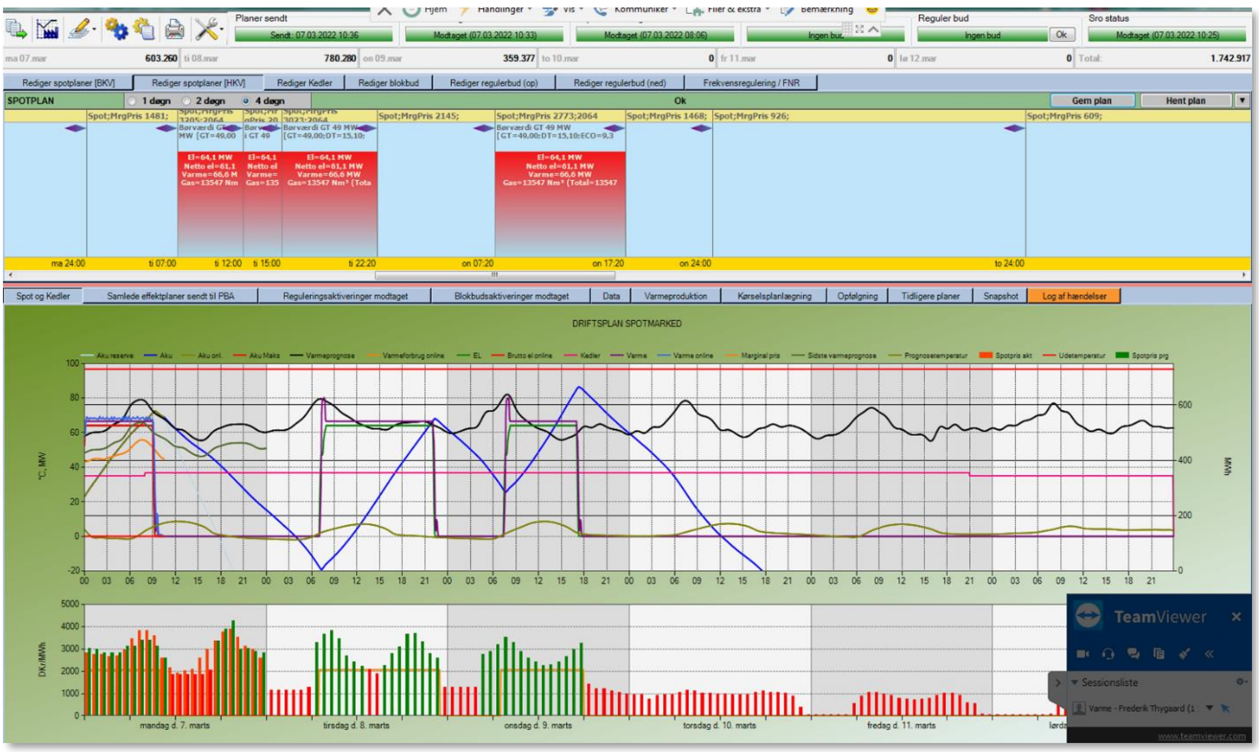

Figure 14: Production plan generated on 07-03-2022 from the existing operation planning tool at Hillerød Forsyning.

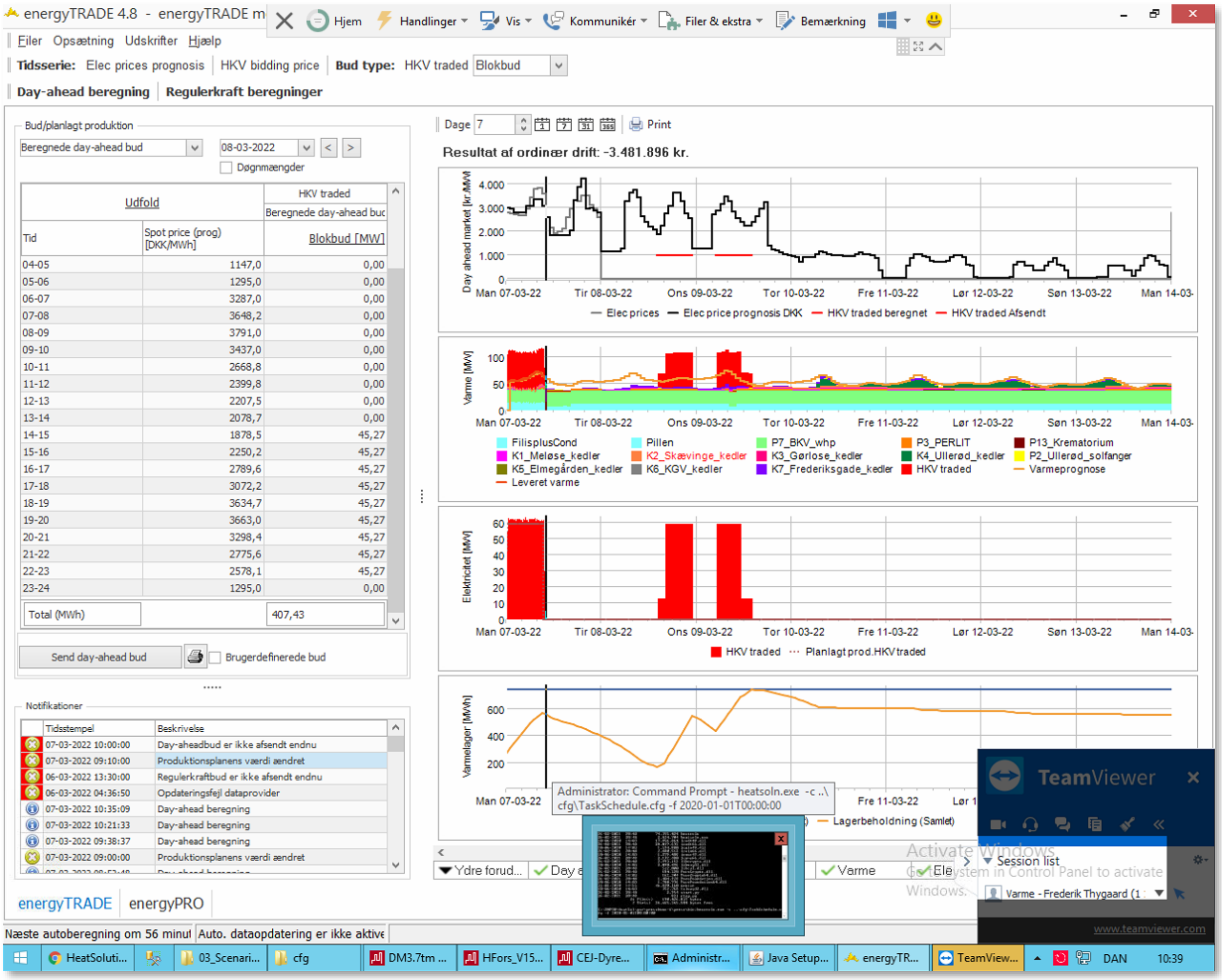

Figure 15: Production plan generated on 07-03-2022 from energyTRADE for Hillerød Forsyning.

Overall, the improvements made to energyPRO and energyTRADE enabled to model the complex plant of Hillerød Forsyning. The work of integration with other partner systems enabled to create a well-functioning energyTRADE model, which included part of the CSO concept, amongst these the heat demand prognosis provided by ENFOR. The model was appreciated by the operators of the plant in Hillerød Forsyning. There is a potential for including full CSO (considering the demand shift in buildings and networks).

4. Heat Load Forecasting & Temperature Optimization in Distribution Network by ENFOR

This chapter reports on ENFOR's activities in the HEAT 4.0 project. In this section, we summarize the work done on the implementation of the commercial product, HeatSolutions, in the demo district heating systems, as well as the development of ENFOR's systems with several improvements concerning the user/partner/project needs.

4.1 Data-intelligent temperature optimization (TO)

HeatSolutions™ (HeatSol) is an integrated portfolio of forecasting and optimization solutions for the district heating sector. The solution consists of MetFor™, which delivers locally-calibrated weather forecasts, HeatFor™ which provides heat demand forecasts, and HeatTO™, which provides temperature optimization of the supply temperature.

The three modules work as an integrated system. MetFor™ makes a local calibrated weather forecast. It is based on 2-3 external weather forecasts which are weighted and combined with local weather measurements. The locally calibrated weather forecast is fed into HeatFor™ and combined with historical demand data to deliver an accurate heat demand forecast. Based on this heat demand forecast and online measurements from the heating network (flow, supply, and return temperature), HeatTO™ optimizes the supply temperature to meet demand, while minimizing supply temperature. By lowering the temperature in the network, the total heat loss from the system is also lowered, resulting in a reduction in fuel usage.

HeatSolutions™ is based on self-learning algorithms that continuously self-calibrate and improve as they receive data from the district heating network, and thereby the system is fully automatic. Ideally, the solution is integrated with local online weather measurements, but can also run solely on meteorological forecasts. It has a data validation module, which ensures that data with errors is identified, corrected or replaced by other values.

HeatSolutions™ is provided with data interfaces that enable SCADA integration through text files, FTP, database access or web services. The data validation HeatSolutions™ can be delivered as a software package which is installed at the district heating operator or as a hosted solution at ENFOR™.

4.1.1 Implementation and evaluation of HeatSolutions

ENFOR has installed the HeatSolutions system at all three demo cases: at Brønderslev Forsyning, at Hillerød Forsyning, and at Trefor in Kolding, providing locally optimized weather forecasts, heat load forecasts, and temperature optimization in the distribution network. This report provides an evaluation exact of each system's performance before and after the HeatSolutions installation. As far as the writer knows, the district heating systems have not undergone significant changes during the period of comparison, so the difference noted during the project can be attributed to the introduction of HeatSolutions.

For each demo case, the supply temperature in the DH network is assessed in comparison to the supply temperature of the previously used control strategy, i.e. before the installation of HeatSolutions. To account for the influence of the ambient weather conditions between the compared periods, the supply temperature is registered against daily heating degree days. The 'Degree day' methodology is a way of representing the ambient air temperature with special emphasis on its influence on heat load. Daily, degree days are calculated as the positive difference between the diurnal average indoor temperature (for Denmark set to 17°C) and the diurnal average ambient temperature. The effect on the return temperature is also observed.

4.1.1.1 Brønderslev Forsyning

Brønderslev district heating system is divided into three sub-networks. HeatSolutions was installed at one of the sub-networks, Skolegade, in September 2019. Integration of the setpoint in the Brønderslev system was confirmed on November 8, 2019.

The HeatSolutions system receives hourly updated weather forecasts and online weather measurements, which are used as input to the heat load forecast. The system receives 5-minute online measurements of flow, load, forward, and return temperature from the central production unit, Skolegade Centralen. The system also receives critical net point temperatures from the Skolegade sub-network and uses this to determine a 5-minute setpoint for the supply temperature according to the guaranteed net point temperature requirements defined by Brønderslev Forsyning.

The HeatSolutions system is hosted externally, by ENFOR, and provides a web-based graphical user interface with access to heat load forecast and temperature optimization, including control settings for the optimization. Figure 16 shows the front page of the graphical user interface of the Brønderslev Forsyning system. Figure 17 and Figure 18 show examples from the graphical user interface of the heat load forecast and the measured and optimized supply temperature setpoint, respectively.

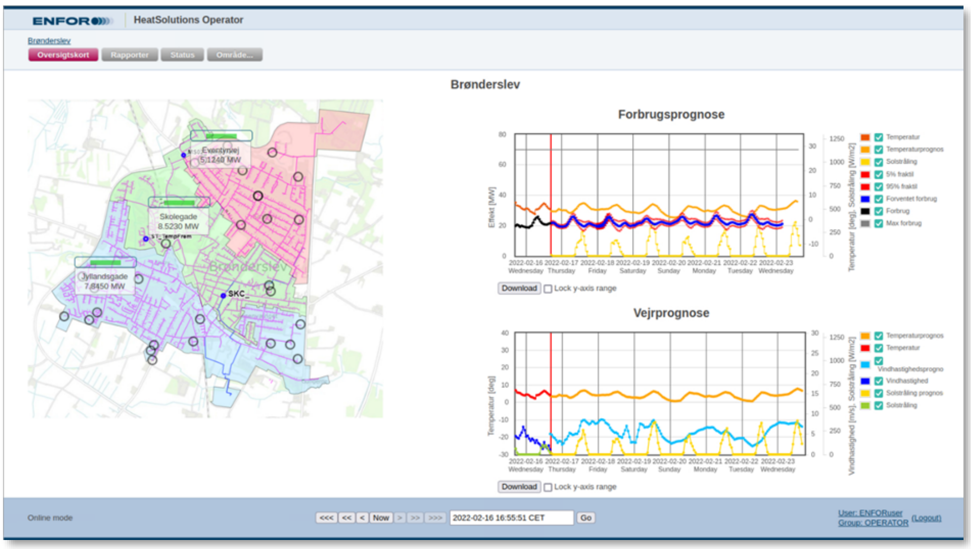

Figure 16: HeatSolutions for the whole DH network in Brønderslev Forsyning. (EN1)

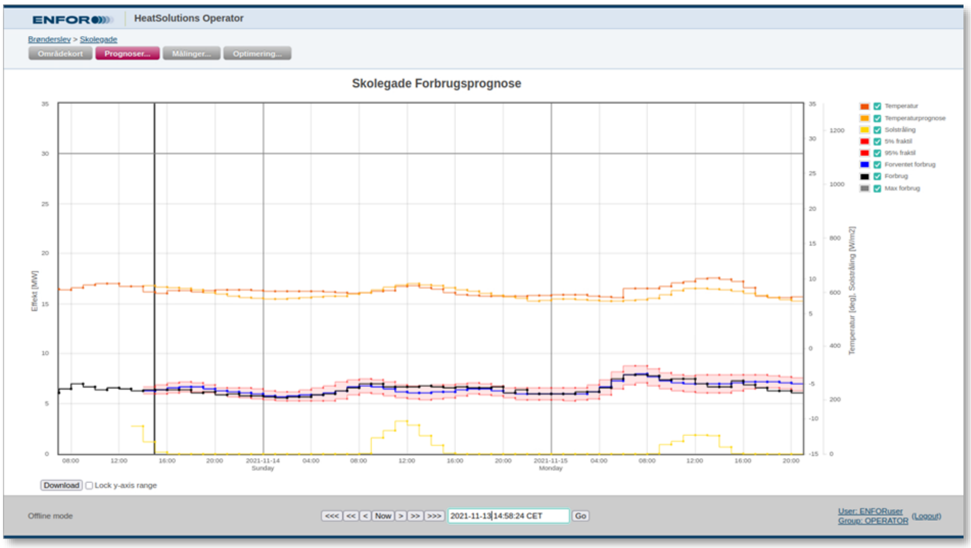

Figure 17: Heat load forecast and measured load for Skolegade, Brønderslev Forsyning. (EN2)

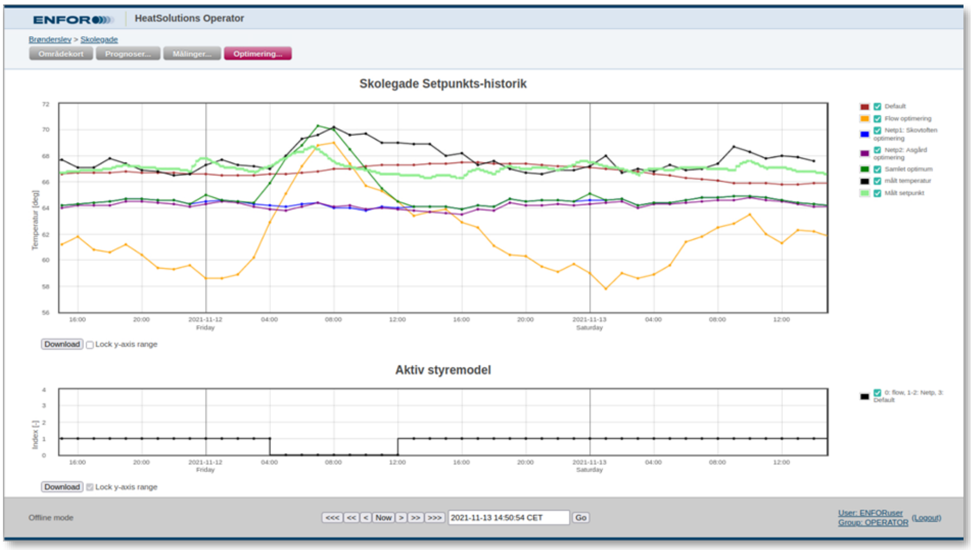

Figure 18: Measured and optimized supply temperature setpoint for Skolegade, Brønderslev Forsyning. (EN3)

After running for the heating season 2019/2020 using the HeatSolutions' setpoint in this network, the results were evaluated and Brønderslev Forsyning decided to buy and implement HeatSolutions in the whole of their network. Brønderslev Forsyning started using HeatSolutions' setpoints for the new sub-networks during spring 2021.

Figure 19, Figure 21, *and* Figure 23 show the supply temperature versus daily degree days for each of the three sub-networks respectively; the period prior to the installation of HeatSolutions is with black colour, while after installation of

HeatSolutions with blue colour. Days after the installation when the DH system didn't follow ENFOR's setpoints are excluded from the evaluation. The temperature reduction is clear for all three networks. For Eventyrvej it is on average around 3°C for the examined periods, for Jyllandsgade it is 3.5°C, while for Skolegade it is 5°C. From Figure 20, Figure 22, *and* Figure 24 it can be seen that the return temperature is almost not affected by the operation of HeatSolutions, and the very slight increase in Eventyrvej is too small to eventually have a negative effect on the energy costs.

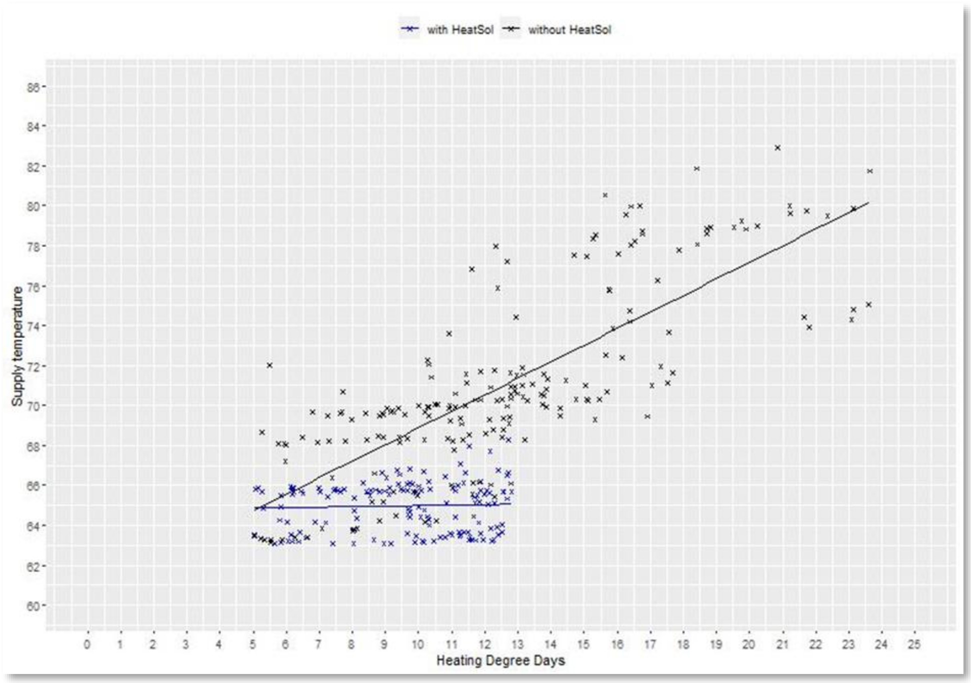

Figure 19: Supply temperature versus daily heating degree days for Eventyrvej. (EN4)

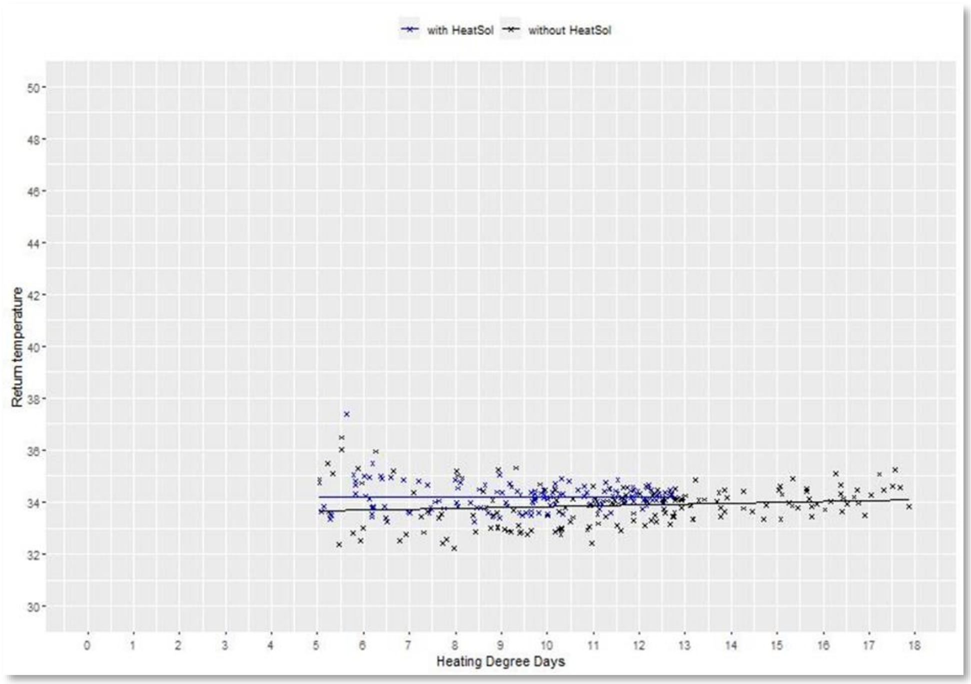

Figure 20: Return temperature versus daily heating degree days for Eventyrvej. (EN5)

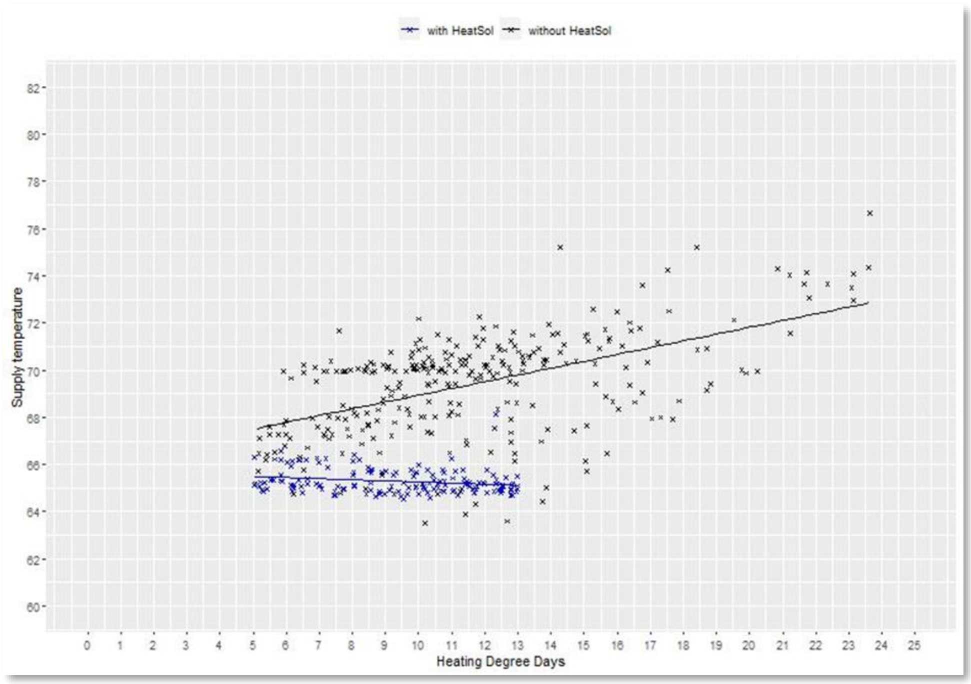

Figure 21: Supply temperature versus daily heating degree days for Jyllandsgade. (EN6)

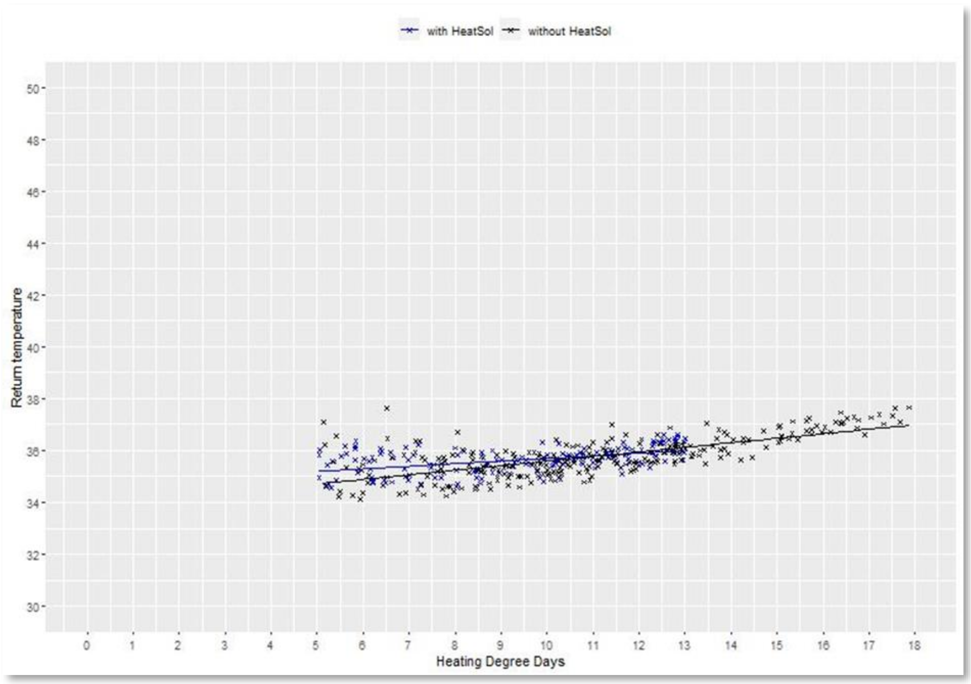

Figure 22: Return temperature versus daily heating degree days for Jyllandsgade. (EN7)

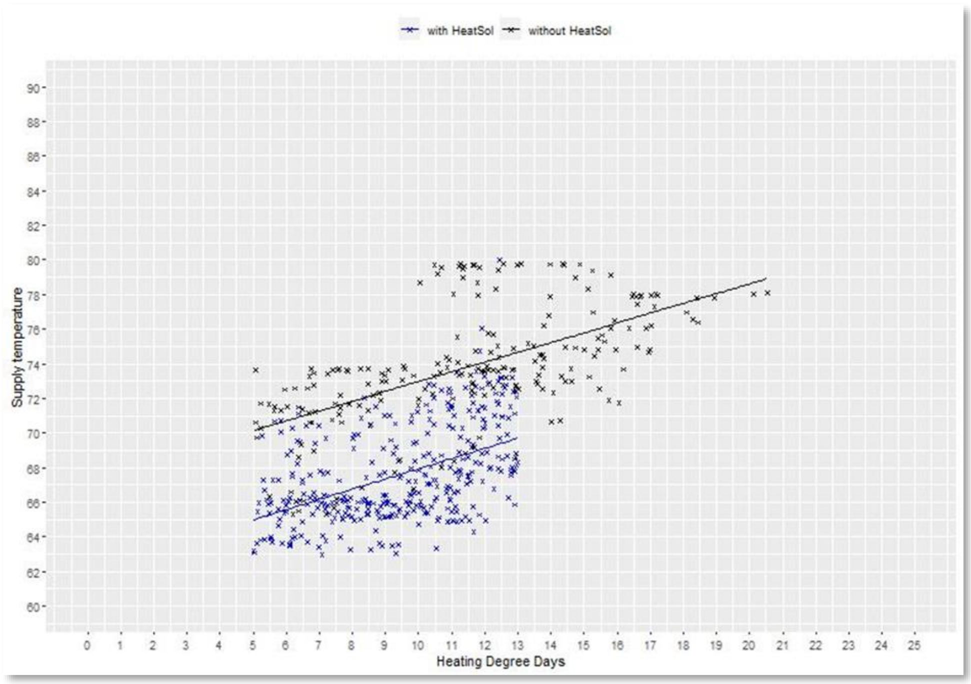

Figure 23: Supply temperature versus daily heating degree days for Skolegade. (EN8)

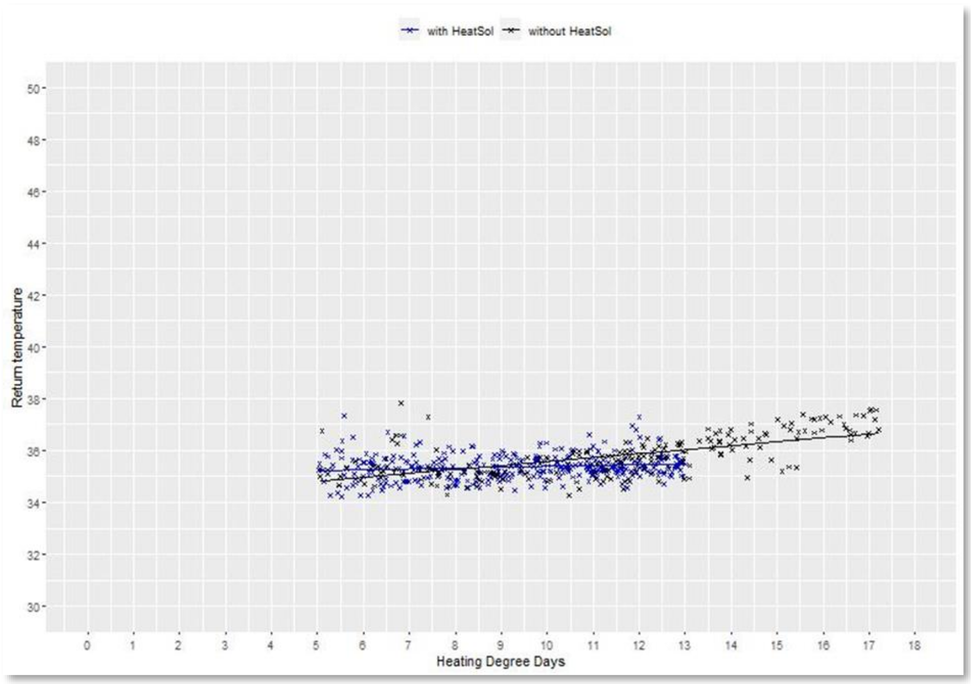

Figure 24: Return temperature versus daily heating degree days for Skolegade. (EN9)

4.1.1.2 *Hillerød Forsyning*

HeatSolutions was installed at Hillerød Forsyning in 2020 for all 7 subnets: Frederiksgade, Kongens Vænge, Elmegården, Gørløse, Skævinge, Meløse, Ullerød. Hillerød Forsyning followed the setpoints provided by the software, though only as a guideline and rather intermittently.

The HeatSolutions system receives hourly updated weather forecasts, online weather measurements and online measurements of load, flow, supply and return temperature from the central supply point of each subnet. For the subnets of Frederiksgade, Kongens Vænge, Elmegården and Ullerød, the system also receives critical net points temperature measurements, which are used to determine a setpoint for the supply temperature according to a guaranteed net point temperature requirement defined by Hillerød Forsyning.

For the other three subnets, Gørløse, Skævinge, Meløse, there are no available measurements for net point temperature. To overcome this obstacle, ENFOR developed a solution, with which HeatSolutions simulates an artificial critical net point to be used for control. This feature was tested in these three subnets of Hillerød Forsyning, and was later finally tuned.

The HeatSolutions system is hosted by Hillerød Forsyning and provides a web-based graphical user interface with access to heat load forecasts and temperature optimization, including control settings for the optimization, for each of the subnets. Figure 25 shows the front page of the graphical user interface of the DH system in Hillerød.

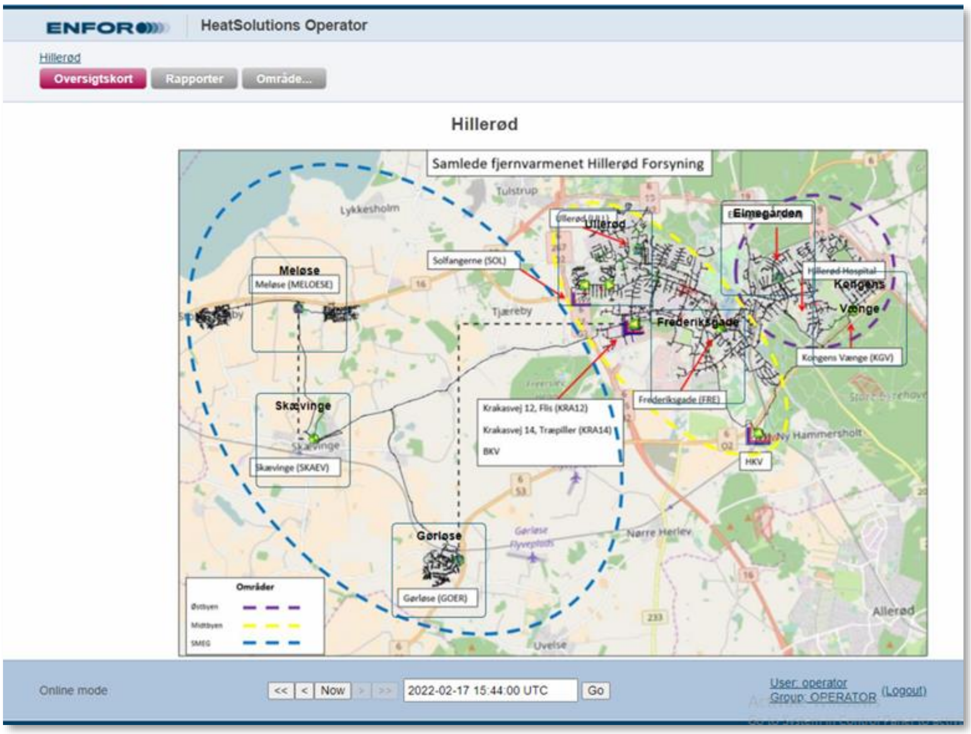

Figure 25: HeatSolutions for the whole Hillerød Forsyning DH network. (EN10)

The evaluation of two networks is presented in this report, Ullerød and Gørløse, where HeatSolutions´s setpoints have been used for longer periods of time. Figure 26, *and* Figure 28 show the supply temperature versus daily degree days for each of the two networks; the period prior to the installation of HeatSolutions is with black colour, while after installation of HeatSolutions with blue colour. Days after the installation, when the DH system did not follow ENFOR's setpoints, are excluded from the evaluation.

The temperature reduction for Ullerød is on average 5.5°C for the examined periods, while for Gørløse it is 4°C. From Figure 27, *and* Figure 29 it can be seen that the return temperature is not adversely affected by the operation of HeatSolutions, but even seemed to have decreased for Ullerød.

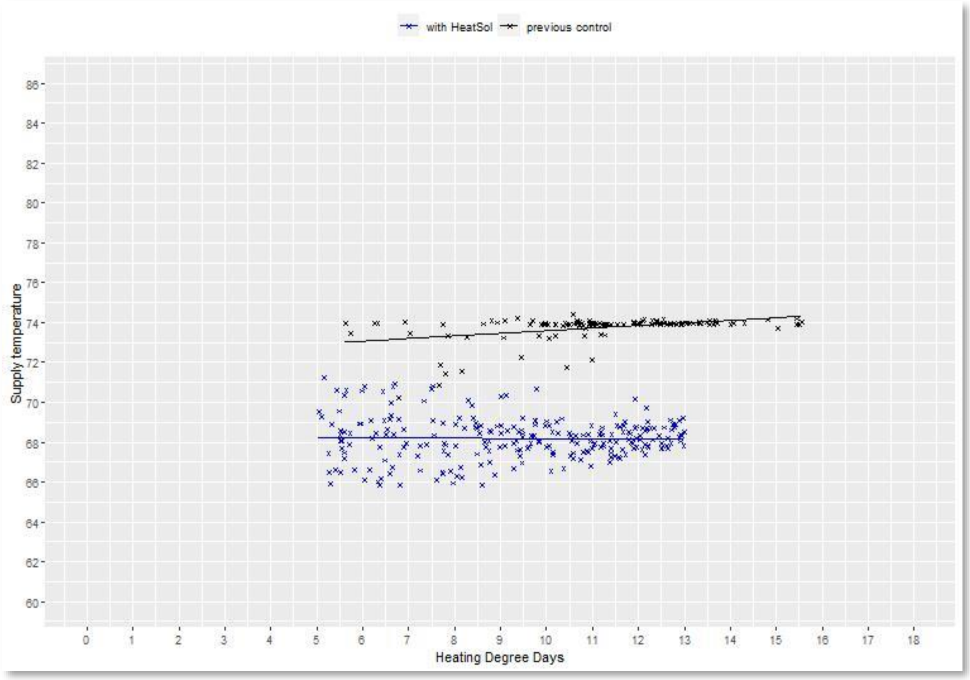

Figure 26: Supply temperature versus daily heating degree days for Ullerød. (ENS11)

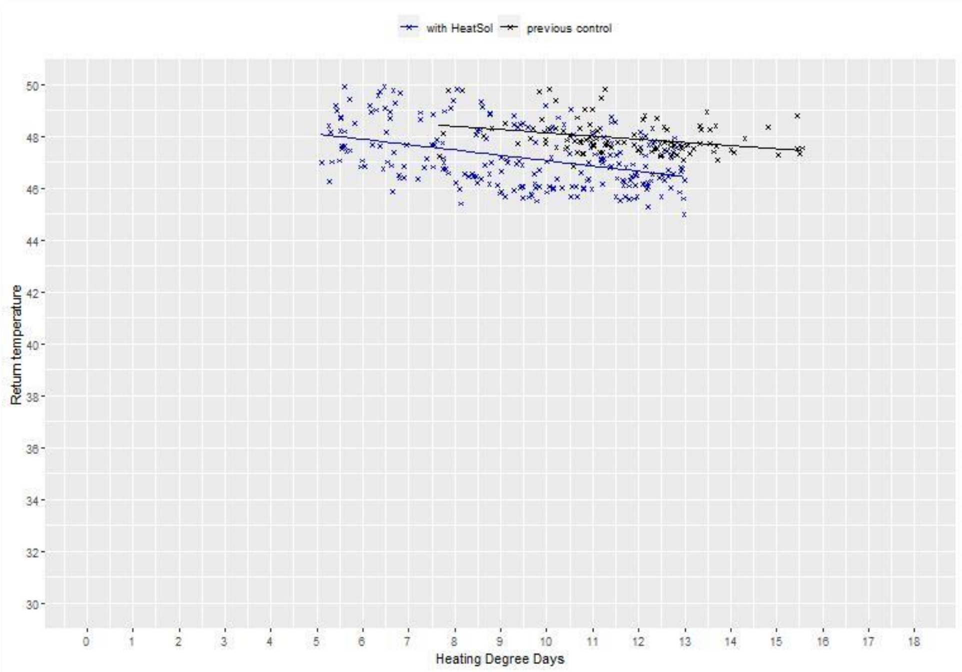

Figure 27: Return temperature versus daily heating degree days for Ullerød. (EN12)

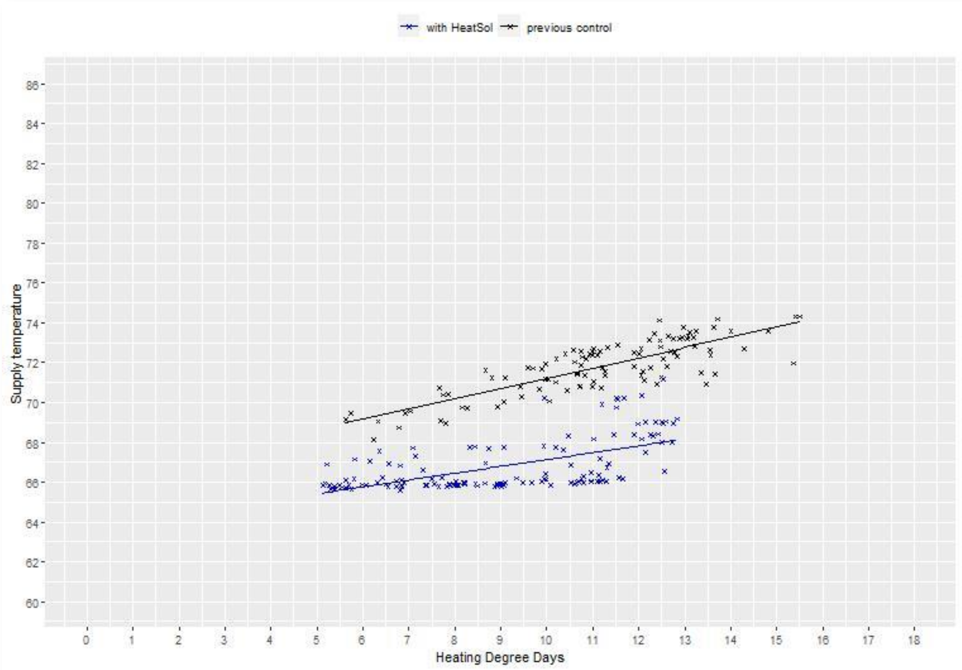

Figure 28: Supply temperature versus daily heating degree days for Gørløse. (EN13)

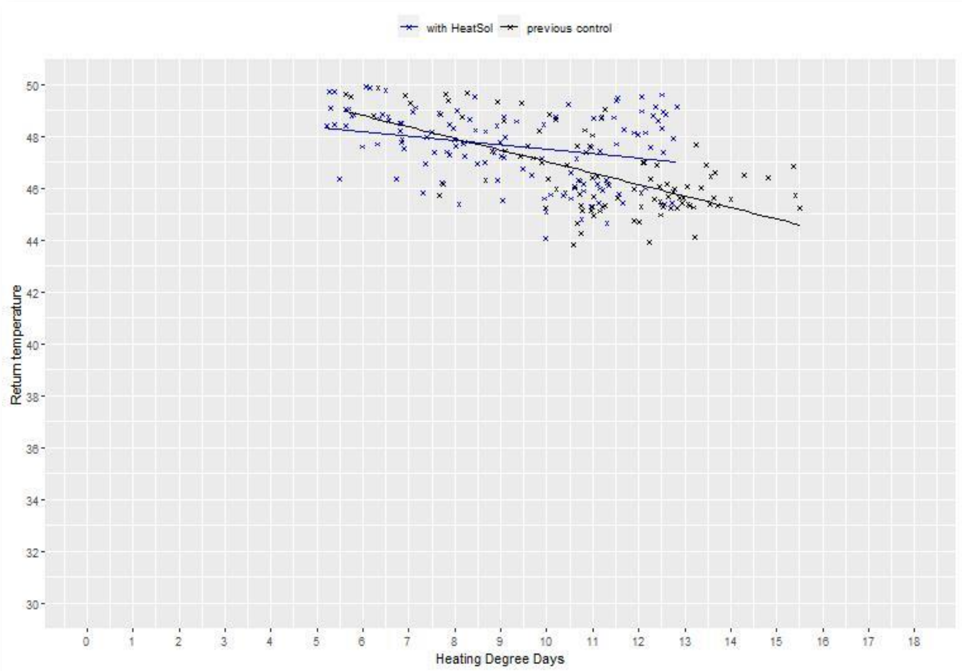

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Figure 29: Return temperature versus daily heating degree days for Gørløse. (EN14)

4.1.1.3 Trefor - Kolding

HeatSolutions software was installed at one of the sub-networks of Trefor, Kolding Syd, in November 2020. Integration of the setpoint in Kolding Syd was confirmed on December 19, 2020.

The HeatSolutions system receives hourly updated weather forecasts and online weather measurements, which are used as input to the heat load forecast. The system receives 5-minute online measurements of flow, load, forward and return temperature from the production units, as well as critical net point temperatures from the Kolding Syd sub-network, and uses this to determine a setpoint plan for the supply temperature according to the guaranteed net point temperature requirements defined by Trefor, Kolding.

The HeatSolutions system is hosted externally, by ENFOR, and provides a web-based graphical user interface with access to heat load forecast and temperature optimization, including control settings for the optimization. Figure 30 shows the front page of the graphical user interface of the Kolding Syd system.

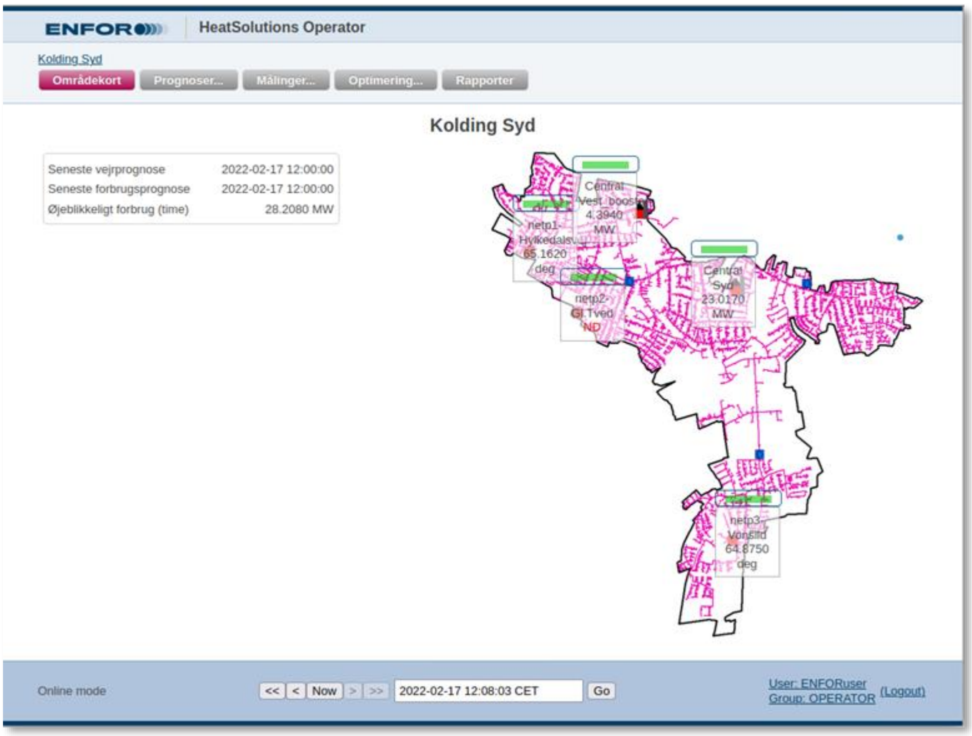

Figure 30: HeatSolutions for the Kolding Syd sub-network of Trefor, Kolding. (EN15)

From Figure 31, a temperature reduction of 4°C on average can be seen for Kolding Syd for the examined periods. Figure 34 depicts a marginal return temperature increase, which is, though, too small to negatively affect the energy costs. Days after the installation when the DH system didn't follow ENFOR's setpoints are excluded from the evaluation.

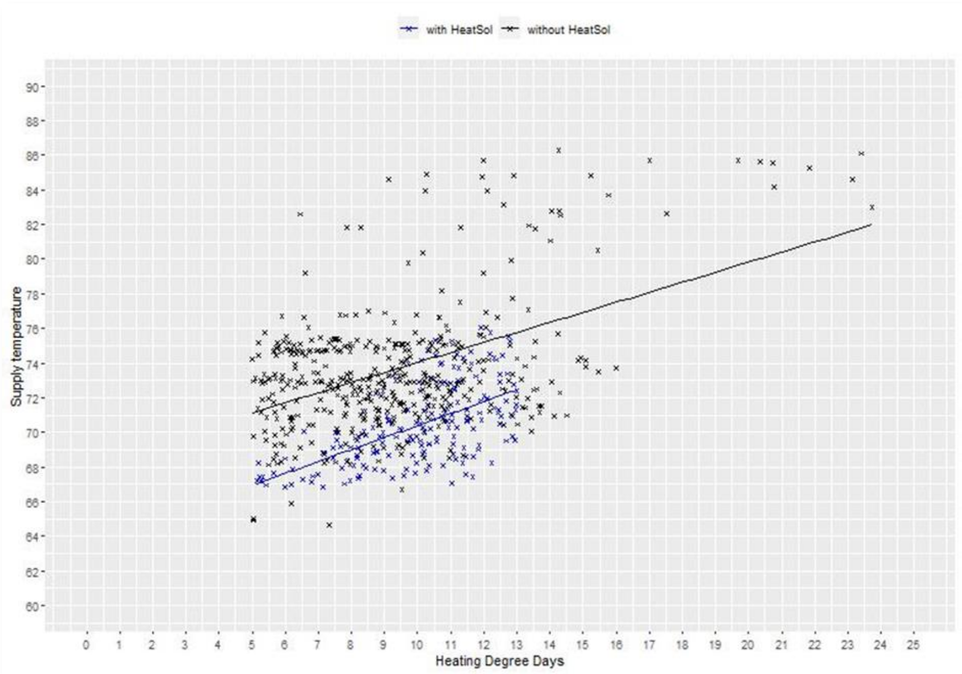

Figure 31: Supply temperature versus daily heating degree days for Kolding Syd. (EN16)

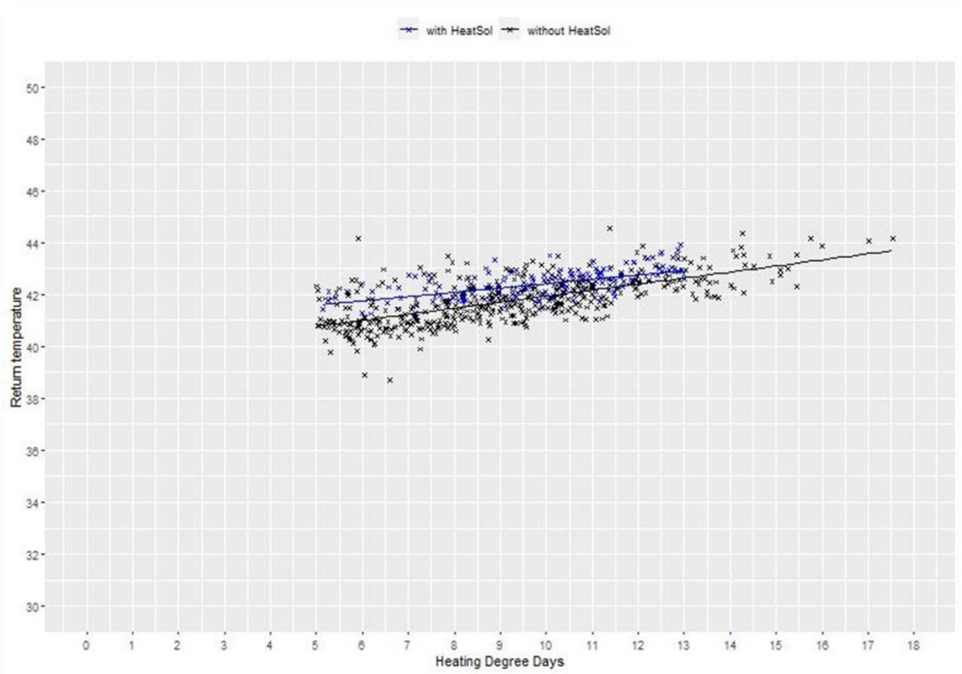

Figure 32: Return temperature versus daily heating degree days for Kolding Syd. (EN17)

After running with HeatSolutions for the heating season 2020/2021 in Kolding Syd, the results were evaluated and Trefor decided to buy and implement HeatSolutions in their entire network. The upscaling work was finalized spring of 2022 and today the 15 sub-networks of Trefor, Kolding are running using the setpoint provided by HeatSolutions. Figure 33 shows the front page of the graphical user interface of the entire Trefor system.

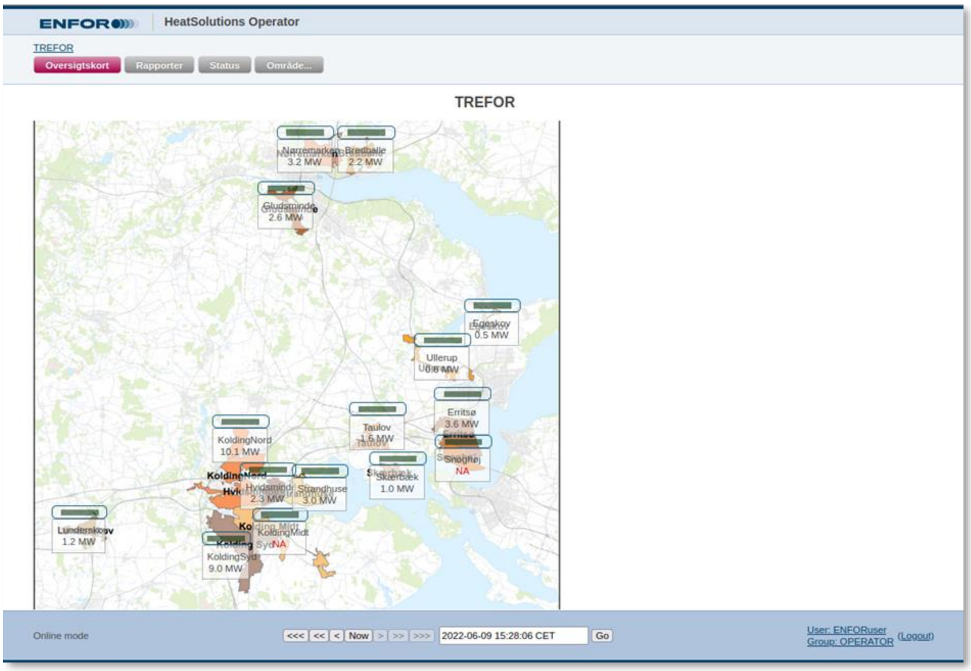

Figure 33: HeatSolutions for the Trefor, Kolding system. (ENnonumber)

4.2 Improvements of ENFOR's systems for the user/partner/project needs

The following paragraphs summarize several improvements due to the HeatSolutions software, related to the HEAT 4.0 project demo district heating systems and the activity of cross system optimization.

4.2.1 Improved weather forecast setup

A weather data setup to support HEAT 4.0 was a large fraction of the work performed for this activity. The work consisted of adding weather forecast sources from meteorological offices, methods for export / extraction of weather forecasts for locations and areas, and archiving of weather data, with the purpose of extraction of historical forecasts for specific locations or areas.

4.2.2 Artificial critical net points

The HeatSolutions system uses weather forecasts, online weather measurements, and online measurements of load, flow, supply, and return temperature from the supply points of a given area. Additionally, it receives critical net point temperature measurements, which are used to determine a setpoint for the supply temperature according to a guaranteed net point temperature requirement, defined by the DH system operators.

For three areas in Hillerød (Gørløse, Skævinge, Meløse) there aren't available measurements for net point temperature. To overcome this obstacle, ENFOR developed a solution, with which HeatSolutions simulates an artificial critical net point to be used for control. This feature was tested in these three subnets and was later finally adjusted.

4.2.3 Artificial critical temperature

DTU Compute and ENFOR have been working together to establish an artificial critical temperature to be used as feedback for temperature control. The artificial critical temperature is computed from a set of smart meters from an area that the district heating operators believe to be the critical point of the network. In the demo case Brønderslev Forsyning, ENFOR has set up their temperature optimization software and has used one of the critical points as feedback for the optimization. Brønderslev Forsyning delivered data from 15 anonymized smart meters and based on these data points an artificial critical temperature was created and compared to the net point critical temperature. The two temperatures time series were almost identical. Eventually, this filter was implemented into the ENFOR software to replace the net point temperature.

4.2.4 Improved seasonal transition

An atypical behaviour of the heat load forecasting model was noticed on a couple of occasions during the seasonal transition periods. The algorithm was improved in this regard, by handling the two transition periods, spring and autumn, differently.

4.2.5 Improvement of hydraulic capacity consideration

Inspired by the discussions with Brønderslev Forsyning, a maximum flow was allowed using online pressure measurements. With the integration of those HeatSolutions, a return pump inlet pressure can be provided as a setpoint to Brønderslev Forsyning, and the optimizer calculates the hydraulic capacity of the network instead of defining it by experience.

4.2.6 Peak load boiler handling

A peak load plant is mostly used to cover peak loads when the base load plant cannot cover the high heat demand. On rare occasions, a peak load plant can act as a reserve plant, for example on occasions where the base load plant should fail. Typically, peak load plants are more expensive heat sources. To improve the temperature optimization, a method to handle base and peak load boilers separately was developed within the optimization algorithm, in such a way that the peak load boiler operation is limited to the minimum. The implementation of this development is in progress and is expected implemented in the Brønderslev Forsyning case within the first quarter of 2022.

4.2.7 Temporal hierarchical modelling

DTU Compute and ENFOR have been working together on the topic of temporal hierarchies on heat demand forcasting. The study done by Bergsteinsson et al 2021[13] was done in collaboration with ENFOR, where data and new knowledge were added to support the analysis. ENFOR also extended that analysis to investigate if similar accuracy results are possible for a prediction horizon of 25 to 48 steps ahead. A similar performance was achieved. These results show that temporal hierarchies can be used to achieve higher heat demand accuracy by forecasting different temporal aggregations levels and sharing information between forecasts.

4.2.8 Controller for peak shaving

DTU Compute and ENFOR have been working together on demonstrating that by utilizing optimal control, the peak effects can be eliminated in the DH distribution. This is done by minimizing the changes in the supply effect as a response to the forecasted heat demands, providing an increase in the stored thermal energy in the system, prior to the peak demands. The peak shaving has been successfully applied to a theoretical test case and is currently being applied to a data-driven test model.

4.3 ENFOR's learnings from the project

ENFOR installed the HeatSolutions software in all three participating DH partner networks.

[13] You find all references in the literature list on https://heatman.dk/publications.

The data integration interface was different for each of the DH systems, and that showed us that it is essential to be highly flexible and support various formats and file types. That is, in fact, an important reason why it was easy to install the system fast and it required very small effort from the DH side. It was possible to install HeatSolutions within the timelines indicated at the planning phase of the project, thus giving us enough time and data to evaluate the results.

After the pilot periods, all district heating companies decided to proceed commercially with the software for all their networks, which will result in a direct economic benefit for each company.

The previous paragraph outlines several developments related to this project, all of which added value to the company's software, making it even more flexible and configurable, to fit most network configurations. A good example of this is the development 6.2.3 - an artificial critical temperature to be used as feedback for temperature control, using smart meters. This development made it possible to implement HeatSolutions to the Sindal district heating system, as described earlier in the report.

Additional learnings came from ENFOR's collaboration with EMD, Leanheat and Neogrid on the cross-system optimization activities. Before the project, ENFOR already knew that the positive economic effect of HeatSolutions is based on the reduction of supply temperature in the distribution network, which is almost directly translated to heat cost reductions. (This temperature reduction was proven for all three DH systems in the project, as analysed earlier). An important learning based on the EMD's simulations is the savings that can be achieved on the production side when lowering the supply temperature at the network.

Along those lines, we already knew the significance of a good heat load forecast, but within the project, we learned about the significance of providing a supply temperature forecast as well as a production optimization tool.

In this report, the results of the cross system optimization activities will be described and the potential is quantified for the times when network flexibility can be activated. Within this work, and with internal developments to the software, it has been shown that network flexibility can be activated without any further investments, once HeatSolutions software is installed.

5. Demand Side Optimization Solution by Neogrid

Neogrid's core competence and commercial offering is within the control of the heating system in all kinds of buildings (from-single family houses to apartment blocks in the residential sector, institutions, schools, and office buildings). Neogrid offers cloud-based energy management systems providing data-driven monitoring and optimized control, aiming to provide benefits on a building level and an energy system level.

5.1 Neogrid's CSO interface

The CSO development participation has allowed Neogrid to design an interface to the network and production side, which allows buildings to cooperate based on the energy system's needs. This interface is based upon a Rest API.

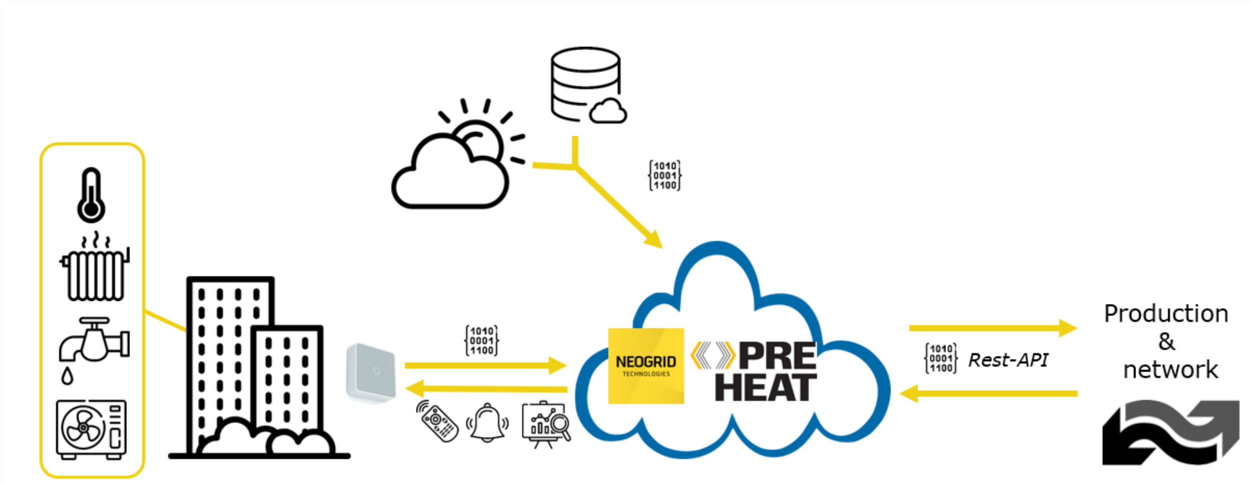

Figure 34: Architecture of Neogrid's solution with CSO interface via Rest API.

This interface provides several predictions, for a given sub-net of interest:

- minimum supply temperature requirement
- expected return temperature
- expected energy demand.

Upon an authenticated request to this API from an authorised third-party (ENFOR, EMD, and Center Denmark as HEAT 4.0 partners), a CSV[14] in standardised format is returned with the following structure.

[14] Comma separated value file type could also be any other delimiter separated file type.

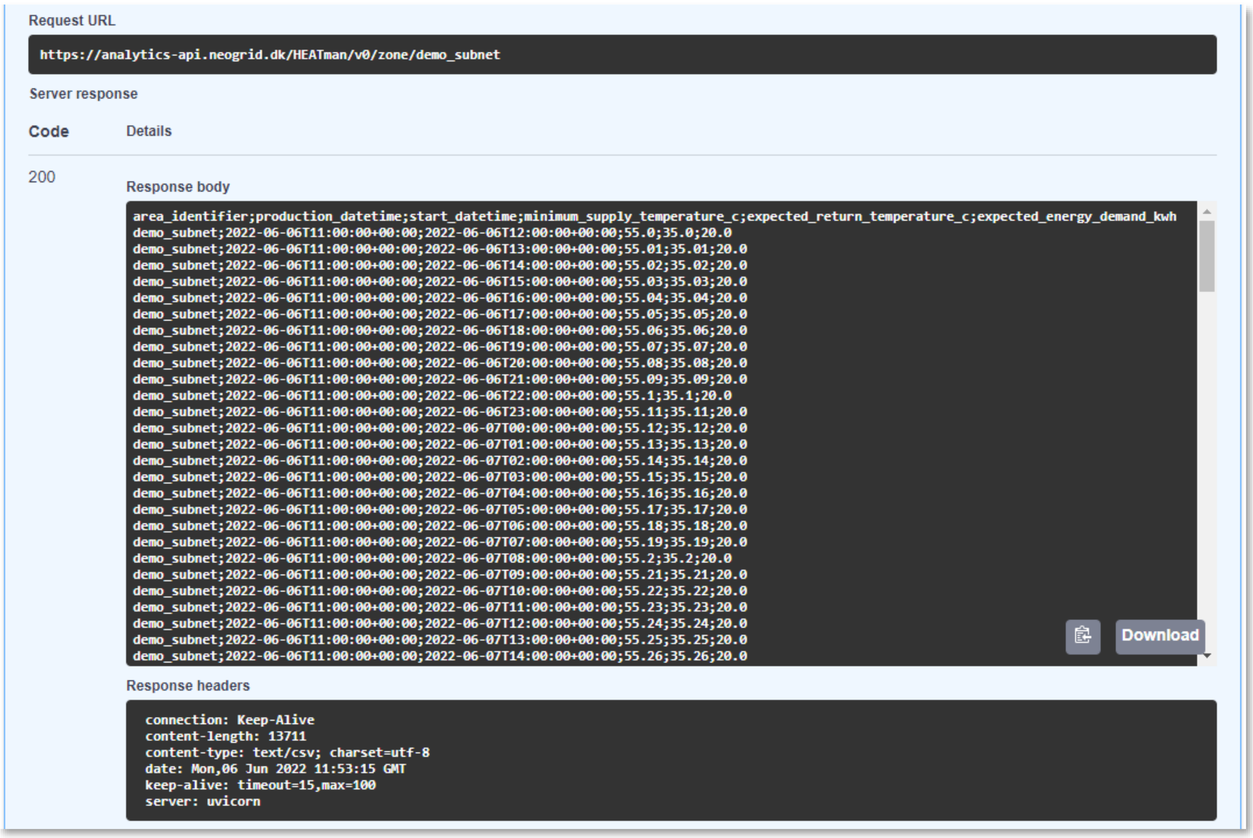

Figure 35: Standardized interface for building to network/production communication via a Rest API (the data is delivered with hourly resolution and a horizon of 7 days ahead) – Note that the data presented here is from a development endpoint, which is available without authentication.

The standardised structure of this CSV-based rest API was defined jointly by the CSO group partners To ensure that it would meet the requirements of their tools. Practical measures on the building side were as well taking into account. The endpoint is mainly a 1-way communication interface from buildings to the district heating system, which allows operators to reduce the supply temperature and optimize according to a refined production forecast.

Together with other partners in the CSO group, another 2-way information exchange protocol concept was developed. Here, the ambition was to create a possible multi-actor optimization based upon successive iterations and sampling of the solution space (both in terms of supply temperature and demand shifting). Such an approach however demanded stronger orchestration of the information exchange and more involved buildings be adequately demonstrated. It was therefore not possible to bring the efforts to a demonstration stage during the HEAT 4.0 project.

5.2 Neogrid's work within HEAT 4.0

5.2.1 Improvement of tools and infrastructure

To be able to take advantage of the latest state of art tools for forecasting, machine learning, and web-API operationalization, Neogrid has transitioned from a Matlab-based environment to a Python-based environment during the HEAT 4.0 project. While being resource intensive, this shift has allowed facilitating operationalization of the models in a production setup, eased fast prototype development, and made modelling and optimization capabilities considerably more flexible. It was also in this Python-based environment that Neogrid implemented the above-presented interface for cross-system optimization.

Furthermore, Neogrid has also made a series of upgrades to its open API for building data analysis and asset control (including open-source Python and Matlab wrappers). This allows a PreHEAT cloud system to be interoperable with 3rd parties (including HEAT partners, e.g. universities and Center Denmark, whenever these are granted access to data from specific buildings), and this is as well a further step into fostering a collaborative and open innovation environment.

In parallel with these activities, Neogrid carried out work in control and condition monitoring developments, achieving a scalable architecture for providing online data-driven operational services. On the monitoring level, this includes the generation of regular performance reports for buildings with complex HVAC systems and online fault detection of central space and water heating provision. On a control level, a semi-automated optimised adaptive heat-curve concept was developed and operationalised, as well as a peak-reducing controller for an aggregate of buildings.

5.2.2 Control at building level

At the building level, Neogrid carried out a demonstration of a series of 4 buildings in Brønderslev Forsyning:

- Two low-energy single-family houses with floor heating
- One institutional building
- One office building

In the institutional building, a reduction of the heat contribution to the system's evening peak was achieved by over 50% (on most days), as shown below.

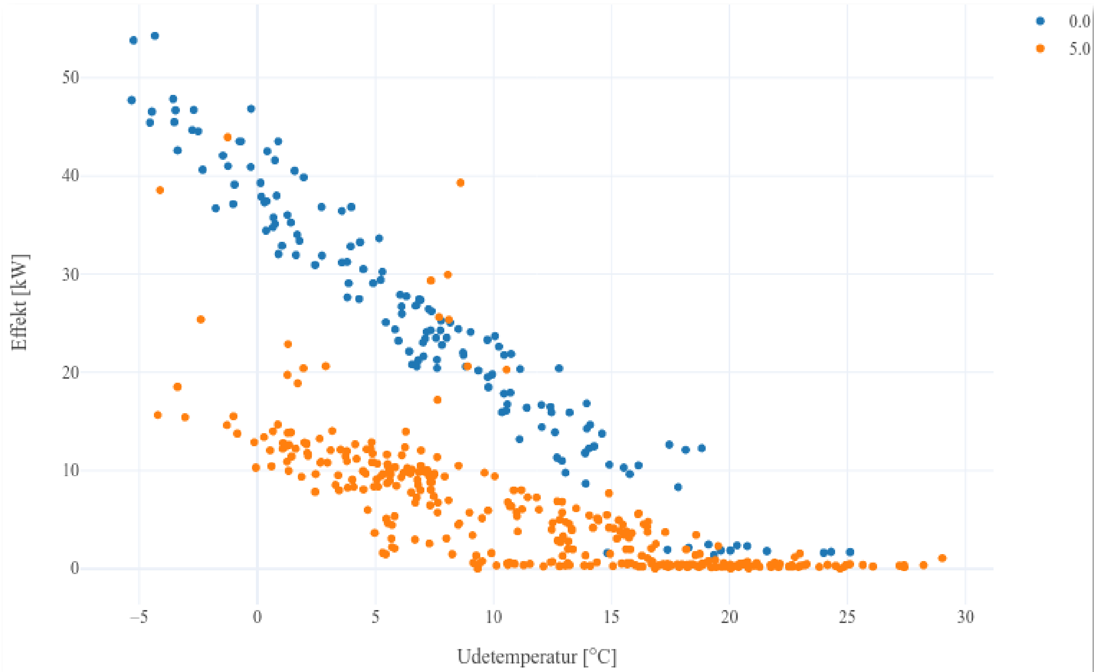

Figure 36: Reduction of the average heat demand of an institution building during the evening peak times (16:30-18:30) for an institutional building in Brønderslev Forsyning (0.0/blue is the original controller, 5.0/orange is Neogrid's optimised controller).

Through this example from a single building, we show that there is significant potential for reducing heat loads of larger buildings to the system's peak load, by optimising the control of the building's heating systems (here by over 20 kW on average on a cold day).

Regarding the two single-family houses, reduction of the return temperatures was achieved by several degrees (by 0-10°C) by reducing the central supply temperature to the space heating for the buildings. It was observed that for low-energy houses, reduction of the supply temperature delivered to the floor heating (by a mixing loop in the substation) 5-15°C was achievable by the optimised controller. Those are again results from a very small sample, yet they suggest a significant potential for the value provided to the district heating system from optimised controllers in individual buildings in residential areas.

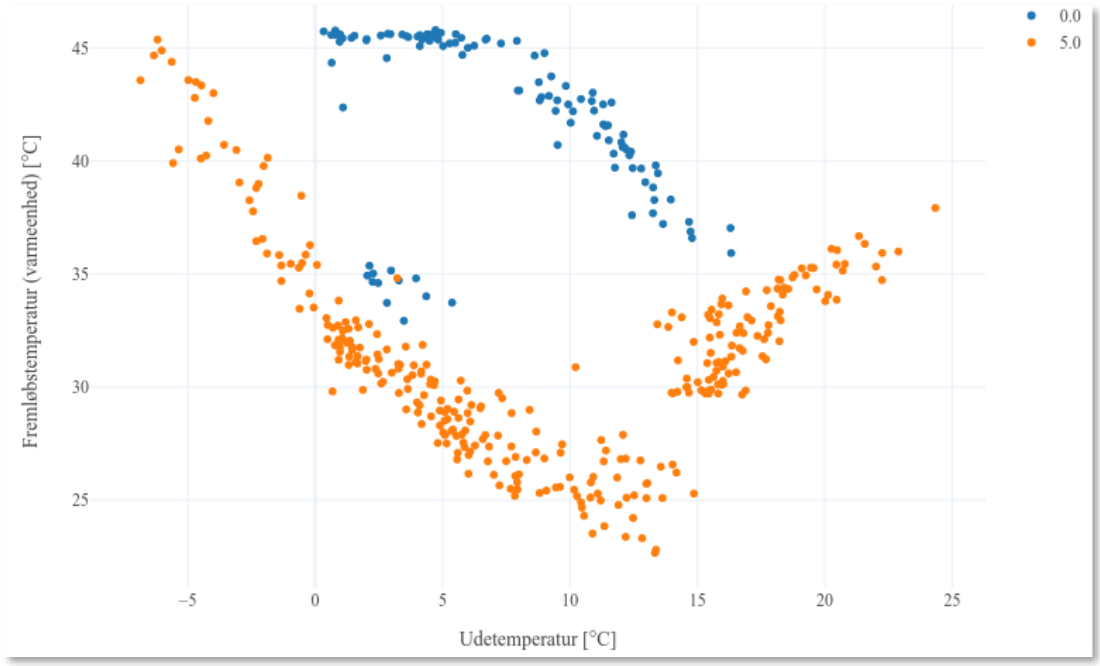

Figure 37: Reduction of the central supply temperature in a low-energy house in Brønderslev, while the required comfort is unchanged (0.0/blue is the original controller, 5.0/orange is Neogrid's optimised controller).

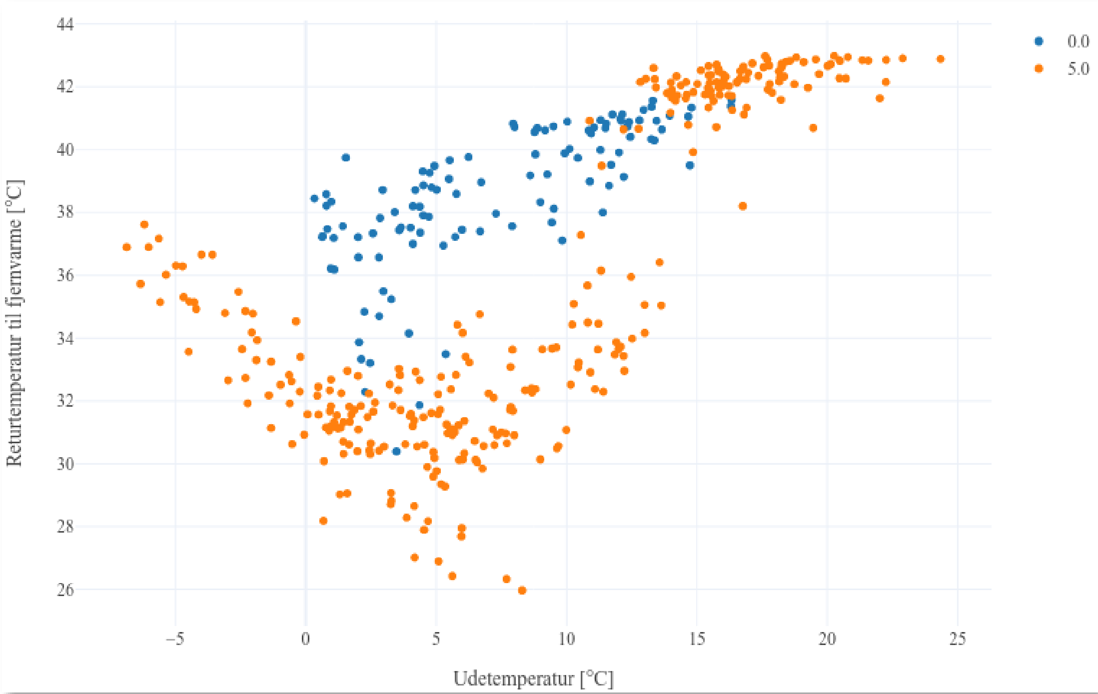

Figure 38: Reduction of the return temperature to the district heating system for a low-energy house in Brønderslev (0.0/blue is the original controller, 5.0/orange is Neogrid's optimised controller).

5.2.3 Developments for aggregates of buildings

Within this project, Neogrid has also developed its capabilities to deal with aggregates of buildings in the district heating system. In the beginning, an aggregator functionality for buildings supplied with district heating was developed, then analysis tools allowing peak management, demand forecasting and further analysis.

A demonstration of peak demand reduction was carried out during the project with promising results (although the test buildings were funded outside this HEAT 4.0 project as it required a sufficient amount of buildings in the same area).

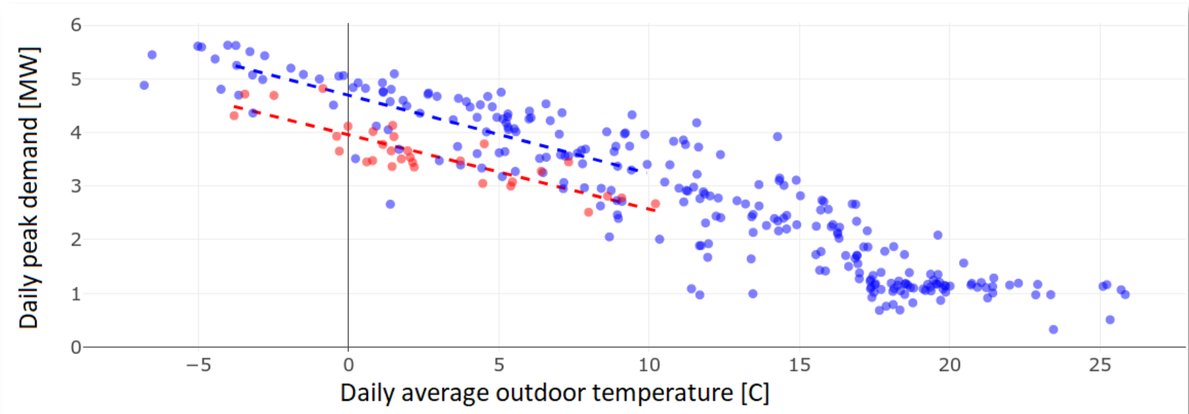

Figure 39: Result of a peak-reduction demonstration on a group of 36 buildings (business as usual conditions in blue, with peak reduction control in red).

In this example, a reduction of the daily peak demand in the range of 20% was achieved, through better coordination of the controllers of the buildings in an area of large residential blocks. Given the typical lack of coordination between controllers in neighbouring apartment buildings, these results are expected to be achievable in other building areas where a coordinating controller is introduced across buildings.

5.3 Learnings from HEAT 4.0 developments by Neogrid

From a building perspective, the strongest bottleneck (by far) concerning CSO is getting sufficient coverage of the buildings in a specific area. This has also been the main limitation for Neogrid in the HEAT 4.0 project itself.

As an example, evaluating the minimum acceptable supply temperature requires that the critical buildings are instrumented. While this might be easily done in areas with cooperative users and well-known problematic installations, it might become quite tedious in areas with many smaller buildings or where the owners of the buildings are not willing to install such a system.

When it comes to energy shifting for peak demand reduction, a similar problem arises, as many of buildings' data need to be aggregated before the amount of energy, that can be shifted, actually starts making a difference for the energy system. This is even more true for low-energy buildings, where the insulation provides a relatively high time constant for storage, but also a much lower amount of energy to be shifted.

Given the low amount of buildings available in the two district heating systems where Neogrid was involved (Brønderslev Forsyning and Hillerød Forsyning), operational results in a CSO context were not attainable. Nevertheless, the technology was developed and operationalized by relying on other buildings available in other geographical locations. Therefore, the technology readiness level (TRL) achieved by Neogrid for the building-level CSO component ended up being lower than initially hoped for.

In a commercial setup, the ratio of efforts required to get into a building (man-hours and installation costs) compared to the return on investment (impact on the system operation, energy saved, income generated by the installation, …) needs to allow for further business development. Given the current low returns, this makes a B2C operation difficult for an actor like Neogrid due to the inherent small volume of such contracts. However, a B2B operation with higher volumes, where services to the district heating network will be combined with services to buildings with a stronger potential for achieving a good sustainable business operation.

6. Demand Side Optimization Solution by Leanheat

Danfoss Leanheat Building is a software solution for optimal control of centrally heated buildings. Leanheat utilizes the latest developments in artificial intelligence and machine learning to automatically generate very precise and accurate mathematical thermodynamic models of the buildings that it controls. The final goal is to control the indoor temperature of the buildings to a specified setpoint within some tenths of a degree. Precise control of indoor temperature saves heat energy, as all indoor temperature volatility associated with traditional heating control strategies is eliminated. This stable temperature control strategy also serves for better indoor comfort and thus healthier living conditions.

Due to Leanheat's predictive control strategy, buildings can be effectively transformed into temporary heat storage without having a bad influence on indoor conditions, which is especially useful if the heating source consists of variable available renewable energy forms. The same principle can also be utilized in demand response solutions for district heating, making it possible for the district heating company to produce heat when it is most beneficial economically or ecologically. Leanheat can also be used to lower the peak power demand of a heating substation by predicting the usage of domestic hot water while adjusting space heating accordingly. Leanheat Building's core functionality is visualized in *Figure 40*.

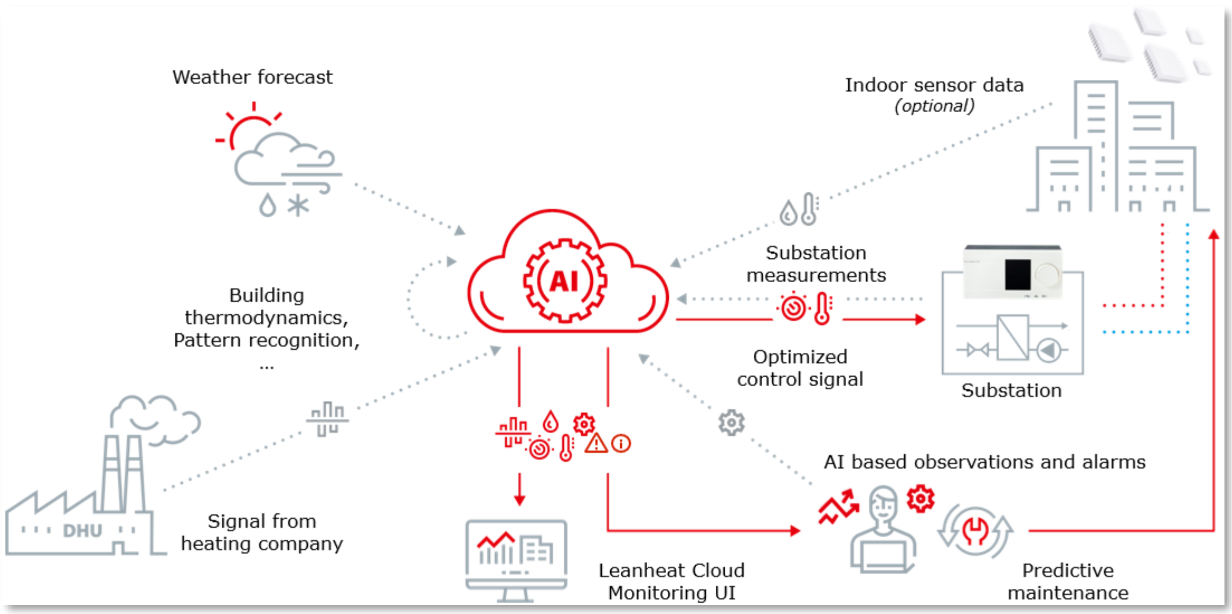

Figure 40: Leanheat AI is self-learning, automated & predictive for optimal control of the buildings. ©Danfoss

Leanheat Oy, Finland was fully acquired by Danfoss during HEAT 4.0 project in 2019 and Leanheat Building solution was merged into Danfoss Leanheat® software suite along with other Danfoss software, i.e., Leanheat Monitoring, Leanheat Production and Leanheat Network. Functionalities in Leanheat software suite are described in *Figure 41*.

In relation to HEAT 4.0 project, Danfoss Leanheat Software Suite is working towards a vision called End to End (E2E) with similar aspects as the CSO development in the project. The focal point of E2E vision is Danfoss Leanheat® suite which offers optimization solutions that harness the power of digitalization to help users in the entire district energy network to increase operational efficiencies, decrease costs, and accelerate the green transition. E2E vision aims at modular and open applications, and thus it also supports collaboration and partnership with other solution providers.

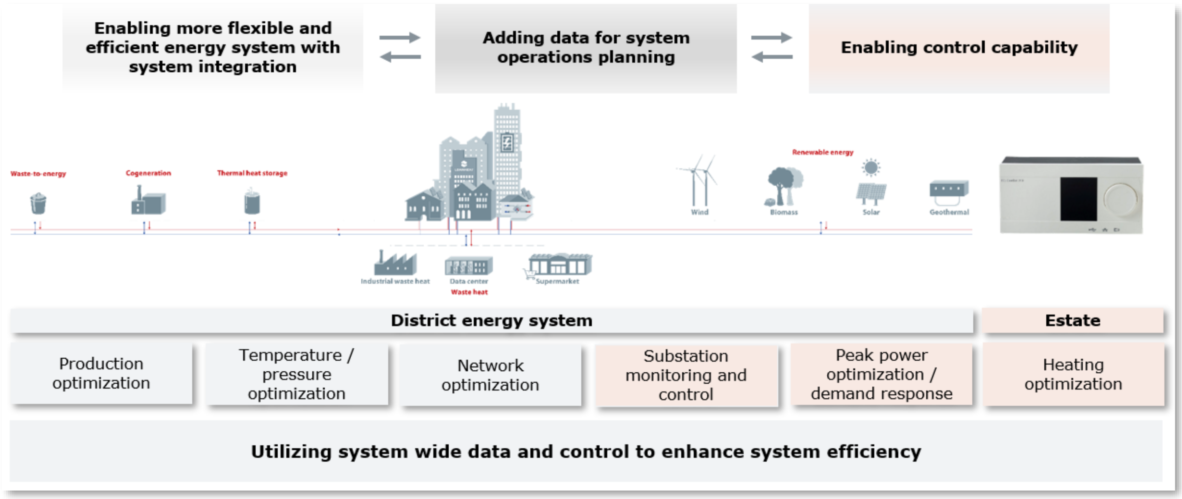

Figure 41: Functionalities in Danfoss Leanheat software suite. Orange coloured boxes represent Leanheat Building functionalities, which have been used in HEAT 4.0 project. ©Danfoss

Leanheat uses two different solutions for building-level optimization in the HEAT 4.0 project, i.e.: Full Leanheat and Sensorless Leanheat. Sensorless Leanheat is commonly used in situations where indoor temperature sensors are difficult to install in apartments. The optimization process differs between the two solutions as depicted in *Table 4*. Previously Sensorless solution did not grant any energy savings and focused only on peak shaving, but Leanheat developed the solution during the project to also incorporate energy savings. Development of the Sensorless solution is further elaborated in the subchapter Leanheat research and development activities. Leanheat operates Full Leanheat solution in 13 multi-family buildings in Kolding and Leanheat Sensorless solution in 12 multi-family in Hillerød.

Table 4: Service and solution descriptions for two Leanheat solutions implemented in HEAT 4.0.

	Full Leanheat	**Sensorless Leanheat**
Estimated results	▪ Energy savings 5-10 % ▪ Peak shaving 10-20 % ▪ Demand response capability	▪ Energy savings 3-6 % ▪ Peak shaving 10-15 % ▪ Demand response capability
Data sources	▪ Weather forecasts ▪ Heating system ▪ Room sensors	▪ Weather forecasts ▪ Heating system
Optimization process	▪ **Optimization based on indoor temperature setpoint** ▪ Learn DHW usage patterns ▪ Optimize heat load profile while maintaining desired indoor temperature	▪ **Optimization based on configurations of a controller and weather forecasts** ▪ Learn DHW usage patterns ▪ Optimize heat load profile while consuming the predefined "heat budget"
Service description	**Complete heating optimization service**, including ▪ Selecting optimal setpoints based on data together with the customer ▪ Continuously configuring each site for the best performance ▪ Technical support ▪ Reporting	**An additional layer of intelligence** to the controller ▪ Optimization on top of the existing controller configurations (heating curve, setback times etc.) ▪ The customer manages controller configurations ▪ Technical support ▪ Reporting

Leanheat interface is based on a REST API, where you make mostly authenticated GET requests and get JSON in response. Leanheat successfully tested data transfer to the Science Cloud with dummy data in 2019 where Science Cloud pulled building-level data from Leanheat API. Real data from actual buildings in HEAT 4.0 was not finalized due to the required level of anonymization of building data from the utilities. Leanheat is not allowed to share any detailed location information on the buildings or sensor data from the apartments, not even with other project partners. This has caused problems with data transfer as it is not possible in Leanheat API to anonymize the sites and their address etc. The development of an anonymization layer requires major development work and ultimately it would not make sense to have completely anonymized data in a real-life operational system, and thus the aggregation layer was not developed in the HEAT 4.0 project.

6.1 Leanheat CSO integration

The main task of the CSO work was to figure out the methods for setting up the communication and optimization between different parties, i.e., production, network, and buildings. Leanheat has had previous experiences in connecting production and building level optimization, and thus CSO development also supports E2E vision of Danfoss Leanheat.

To be able to provide a significant amount of flexibility from the buildings suited for the needs of production or network optimization, building-level data needs to be aggregated. For this purpose, Leanheat developed an aggregation layer, namely Virtual Heat Storage (VHS). Leanheat VHS combines flexibility from several buildings to one aggregated set of properties and individual VHS's can aggregate the data for both individual subnets and total network level. VHS provides data on the current and forecasted energy and power state of Leanheat controlled buildings as well as offers available flexibility from the buildings in terms of energy and power. *Figure 42* depicts the communication of Leanheat VHS. Data series include for example:

- Available power up/down (kW)
- Available energy up/down (kWh)
- Leanheat-control forecast (kWh)
- Leanheat-control + power request forecast (kWh)
- Total consumption (kWh)
- Energy storage state (kWh)

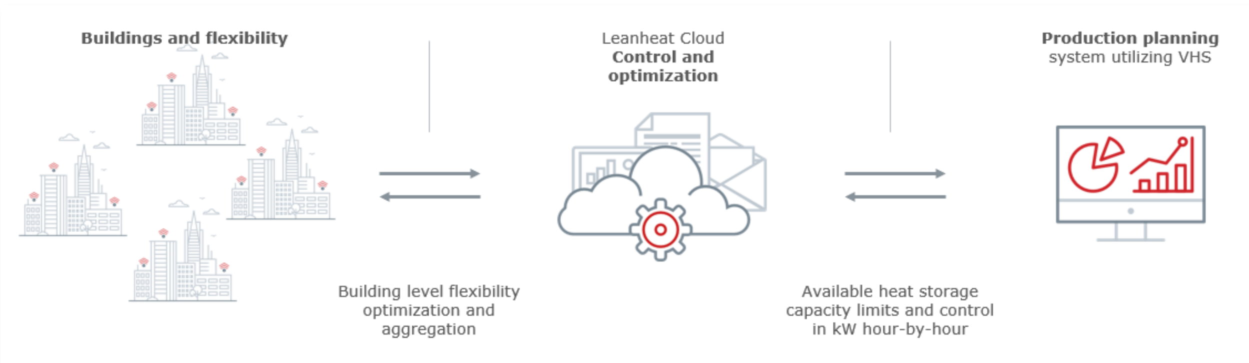

Figure 42: Illustration of communication with Leanheat VHS.

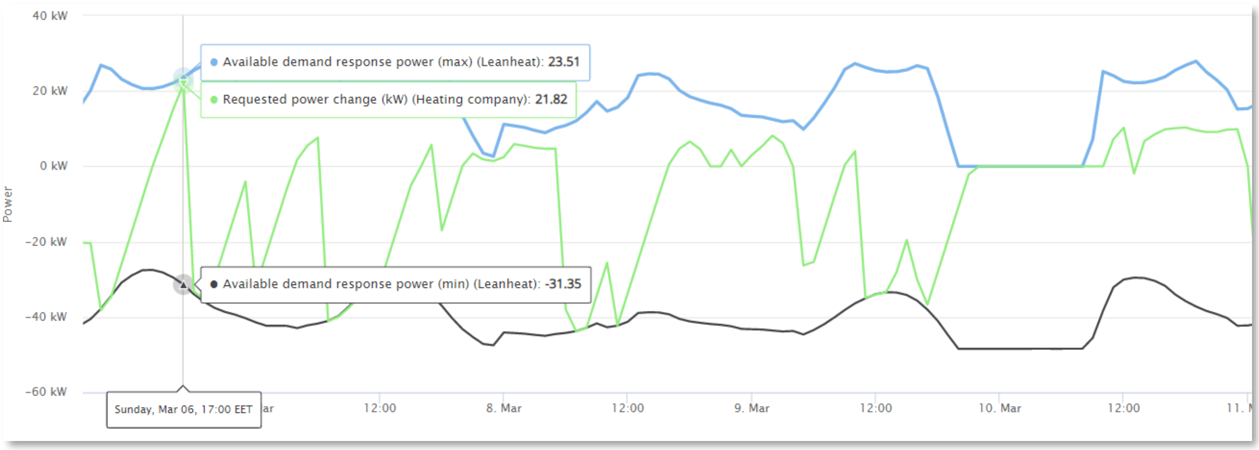

Figure 43: Representation of VHS in action at a site-level in Finland. Blue curve depicts the available hourly charging power limit in kW, while black curve depicts discharging power limit in kW. Green curve depicts flexibility requested by the production optimization for a single site. Screenshot from Leanheat Cloud.

VHS was developed as an extension to the existing Leanheat API. As VHS is available through the same REST API as the building data, the issues with anonymization also affect data integration. Regarding CSO development, the participants formed a list of required data series for one-way dataflow from buildings to production or network optimization. The CSO group also agreed on a standard structure for a CSV-based REST API allowing smooth data flow on an aggregated building-level. Leanheat has worked on developing VHS REST API according to the agreed structure, although Leanheat API is based on JSON format. JSON and CSV structure are mainly aligned, even though a JSON-CSV conversion might be required. Leanheat still has some minor issues to develop regarding common structure in VHS, but ultimately, Leanheat VHS should be ready for integrating with the Commercial Cloud in technical terms.

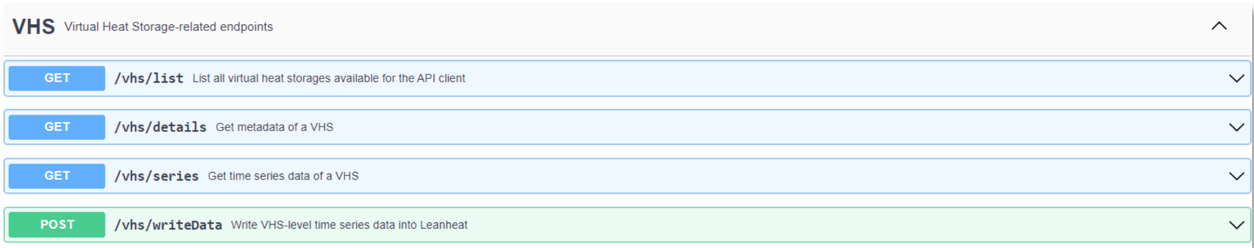

Figure 44: VHS related endpoints in Leanheat API. GET requests are are used for data related to the current state of VHS sites such as available flexibility and POST request used for sending signals from production when to utilize flexibility. Forecasts are available for a rolling 7-day period.

Furthermore, Leanheat was involved in assessing the value provided by the CSO solution. The CSO group decided to address the value of flexibility in Brønderslev Forsyning as it was the only network where each part of the district heating system (production, network and buildings) was covered and in operation. Since Leanheat is not present in the Brønderslev case, the simulations were driven by EMD, ENFOR and Neogrid. Leanheat provided insights and learnings from their existing cases to the simulations. The topic and potential of buildings and their flexibility were addressed in collaboration with Neogrid and Leanheat.

6.2 Leanheat research and development activities

In addition to the CSO workstream, one of the most important development activities during the HEAT 4.0 project was incorporating a new energy savings module for Sensorless control as it was of high interest to the district heating utilities. Based on the extensive amount of data that Leanheat has gathered from all sites, Leanheat learns how external heat sources affect apartments, and thus Leanheat can decrease supply temperature on the secondary side without decreasing indoor comfort, even without indoor temperature measurements. The expected energy savings are lower than in the regular Leanheat, but Leanheat estimates the savings to be between 5-10%. The new module has been in use on Leanheat's sites in Hillerød since the control started in late 2020. Leanheat will continue the development of Sensorless based on the learnings from the project, including the capability to use Sensorless sites in the context of VHS to be able to offer aggregated flexibility in Sensorless buildings.

Leanheat has also participated in Domestic Hot Water (DHW) tank operation principles and optimization workstream driven by Danfoss and DTU Byg. The aim of the workstream is to analyse new potential benefits from optimizing both the radiator network and DHW tanks for improving, for example, return temperatures. Research is conducted on two sites in Hillerød, in which Leanheat is optimizing the supply temperature of space heating. DTU Byg is studying how to optimize DHW tanks better and Leanheat has provided information and data from the space heating circuit to supplement DTU Byg's research. Danfoss and Leanheat published a conference abstract at Smart Energy Systems (SES) conference in 2021 together with DHUs on findings from the sites where Danfoss studies DHW patterns and Leanheat is controlling space heating simultaneously.

As CSO could not be demonstrated and actuated in any of the test systems, CSO group decided to analyse what would be the impacts of the Leanheat controlled buildings for networks in terms of lowering primary side supply temperature in case they would be used as a representation of a single subnetwork. Leanheat controlled buildings are not the most critical buildings in the network so a potential decrease of primary side supply temperature with a controlling secondary side cannot be actuated in real life.

During the analysis phase, Leanheat calculated the required minimum primary side temperature needed in the secondary side. Analysis was carried out for both Trefor in Kolding and Hillerød Forsyning from 1.1.2021-14.5.2021 and Leanheat calculated the theoretical required DH supply temperature for each hour during the period. The aim was to create a simplistic method by using the experiences on other Leanheat sites to define the minimum required supply temperature based on the maximum of individual sites. The following assumptions and constraints were applied in the analysis:

- DH supply temperature needs to be at least 5C above TE1 (secondary supply) due to HEX efficiency
- The minimum primary side supply temperature is set to 60C, which is the minimum temperature that is promised to customers
- DH flow rate cannot exceed - measured realized maximum
- DH consumption stays the same
- DH return temperature stays the same

The analysis shows that primary side supply temperature could have been reduced on average by 3.9C and 6.2C at Trefor in Kolding and at Hillerød Forsyning, respectively. Daily average temperatures show possibilities for Hillerød Forsyning, and Trefor in Kolding and are presented in *Figure 45* and *Figure 46*. In theory, this could generate significant savings for the District Heating Units (DHU), however as stated before, the buildings do not represent the subnetworks well enough. Anyhow, for these buildings the primary side supply temperature is clearly excessive and there could be some room for decreasing the primary side supply temperature with better visibility on what is happening on the secondary side.

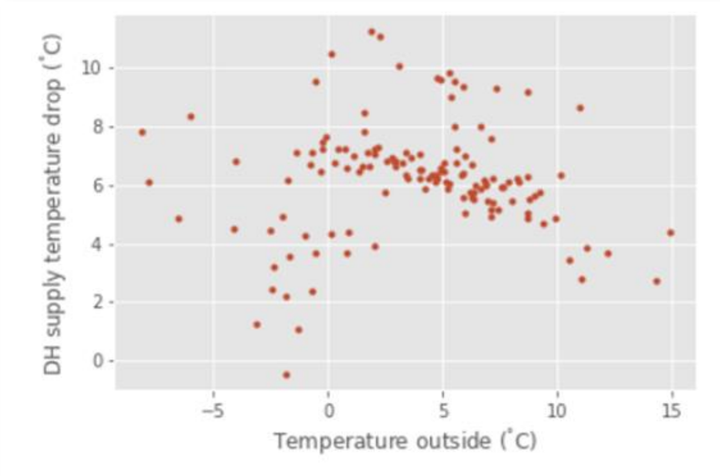

Figure 45: Hillerød Forsyning - potential daily primary side temperature reduction in terms of outdoor temperature 1.1.2021-15.4.2021. Red plots depict hourly potential for decreasing supply temperature in different outdoor temperatures.

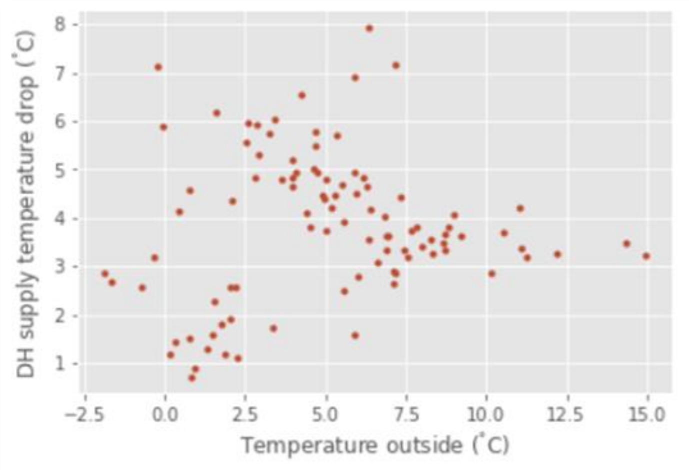

Figure 46: Trefor Kolding - potential daily primary side temperature reduction in terms of outdoor temperature 1.1.2021-15.4.2021. Red plots depict hourly potential for decreasing supply temperature in different outdoor temperatures.

6.3 Improvements to buildings in district heating networks in Kolding and Hillerød

Leanheat building optimization has been running and the improvements in the district heating systems are analysed in the context of energy savings for both Trefor in Kolding and Hillerød Forsyning as well as peak load reduction in the context of District Heating Hillerød. Energy savings were compared based on historical consumption obtained from the district heating utilities. To be able to compare the results of different heating seasons, consumption was normalized by using the heating degree day method where heating degree data was obtained from Danish Meteorological Institute (DMI).

Energy savings results of Leanheat control were analysed for sites in Kolding for the time period where Leanheat was controlling the sites in both 2020-2021 (December-May) and 2021-2022 (September-May). For one site it was not possible to analyse the energy savings due to unreliable consumption data. Individual savings for twelve sites are presented in *Figure 47*. Change in energy consumption on individual site level varied between -9.7% and + 2.4%. The average normalized total energy consumption decrease across thirteen sites was -2.8% (60MWh) and -4.2% (131MWh) in 2020-2021 and 2021-2022, respectively. Savings increased in the second heating season, since Leanheat was operating for the whole season but also because more data were available for the model. As Full Leanheat is controlling Kolding sites based on actual indoor temperature, Leanheat has put heavy emphasis on indoor comfort. To ensure good indoor quality, Leanheat has increased average indoor temperature targets in several sites To avoid resident complaints. This in general has led to lower energy savings than expected.

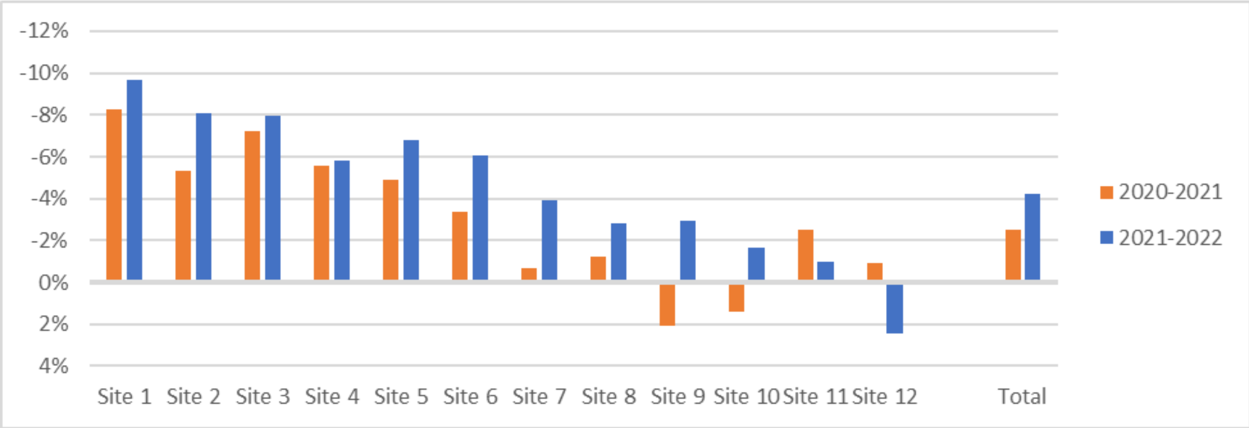

Figure 47: Normalized energy consumption changes per site in Kolding with Full Leanheat compared to 2019-2020. One site was excluded due to poor data quality.

Energy savings results of Leanheat Sensorless control in Hillerød have been analysed for two heating seasons in collaboration with Hillerød Forsyning. Energy savings were analysed for sites in Hillerød for the time period, where Leanheat was controlling the sites in the two heating seasons during 2020-2021 (January-May) and 2021-2022 (September-May). Leanheat were able to analyse data for 9/12 sites due to missing data for other sites. Individual results are presented in *Figure 48*. Total energy consumption on individual site levels varied between 25% and -2%. Average normalized total energy savings across thirteen sites were 8% (101MWh) and 10.5% (202 MWh) in 2020-2021 and 2021-2022, respectively. Savings have increased in the second heating season and, in general, savings for Sensorless control were higher than expected.

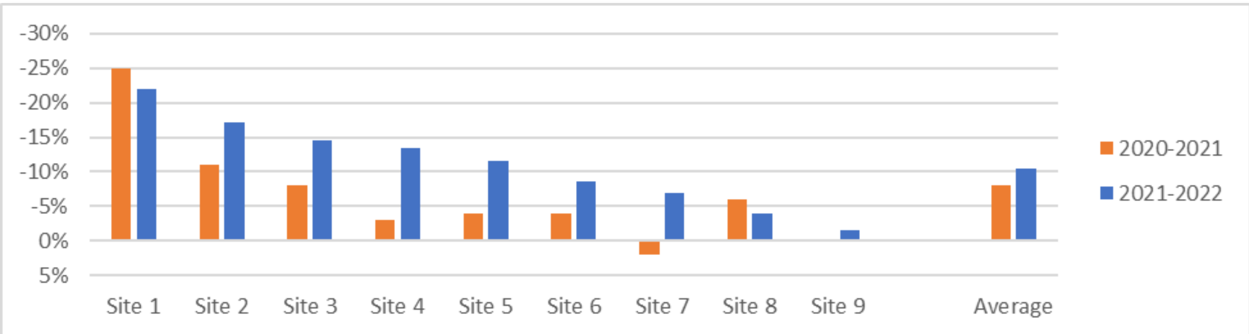

Figure 48: Normalized energy consumption changes per site in Sensorless control at Hillerød Forsyning compared to heating season 2019-2020. Control period was much shorter in the heating season 2020-2021 than in 2021-2022.

In both cases, energy savings are presented from the total energy consumption including both space heating and domestic hot water (DHW) which is not optimized by Leanheat. Results are in general good, however as Full Leanheat sets a target for average indoor temperature defined by the building owner and residents; comfort is the main priority. Sensorless control on the other hand provided better results than expected. It must be noted that Leanheat replaced heat controllers in almost all buildings, which might have effects on the savings if new controllers had been configured differently than previously. All in all, while energy savings and decreasing energy consumption are also in the interests of district heating utilities for obtaining environmental goals, ultimately the energy savings are more important for the building owners, as well as residents who can see the energy savings in decreased energy bills.

Hillerød Forsyning set peak load reduction as one of the main objectives in the first heating season due to challenges in heat supply during the coldest periods. Peak power optimization in Sensorless control aims to shift load from hours with high power, which are typically between 8-11 and 16-18, to times where the load is lower To minimize the highest peaks. Due to the low amount of historical data on power consumption on a daily level, Leanheat and Hillerød Forsyning decided to have short periods in regular non-Leanheat control to be able to analyse the effects of peak power optimization. The sites were in local control on 15-22.2.2021 and 2.3-5.3. Leanheat also used the limited data set that Leanheat had from the sites before Leanheat control was started.

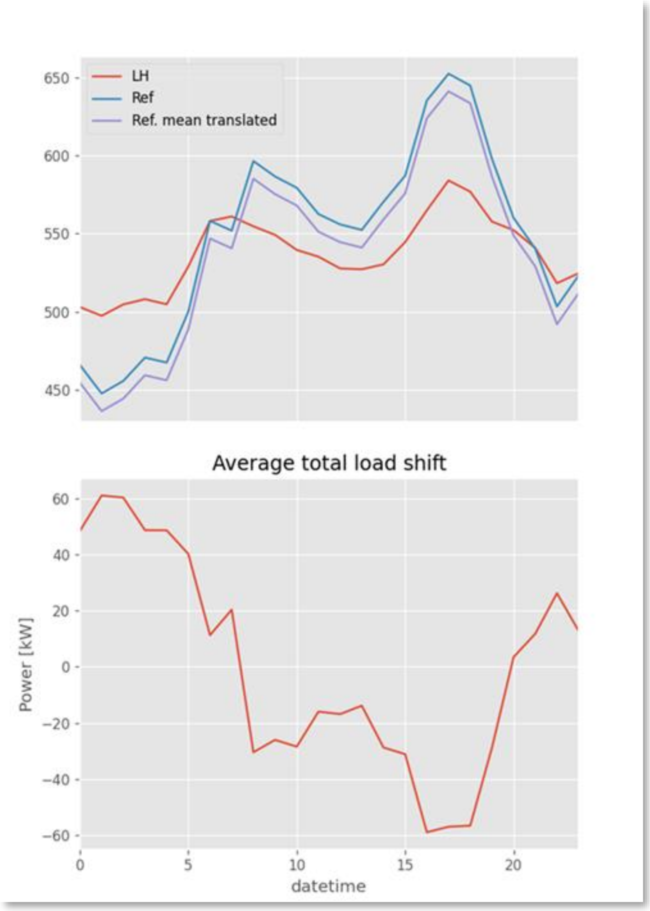

Figure 49. Average daily peak power optimization across ten sites. X-axis depicts hours of one day, while Y-axis depicts the total hourly power in 10 sites. The red curve in the upper figure depicts the total power in Leanheat control while Ref depicts the total power in regular non-Leanheat control. Ref. mean translated curve represents the total curve in regular non-Leanheat control, where the Ref curve is fitted with the same average power as during Leanheat control. Average total load shift per hour is then LH curve – Ref. mean translated.

The peak load was analysed in ten sites and the results were aggregated on an average daily level. The results for the aggregated power are presented in *Figure 49*. On an average daily level, Leanheat was able to decrease 9% of the load from the highest peak, which occurred on average at 17.00. Based on the average daily profile Leanheat was able to decrease the highest peak from 641kW to 584kW in ten buildings in terms of power.

6.4 Insights from other Leanheat related projects

Although CSO tests were not possible to demonstrate in a HEAT 4.0 context, Leanheat has other ongoing projects regarding CSO and Virtual Heat Storage (VHS). Currently, Leanheat has several projects where Leanheat is piloting VHS, and buildings are directly connected to the production optimization software. Building-level optimization has been directly integrated into four different production optimization software mainly through VHS but in one case the aggregation layer is separately developed by the district heating utility. Currently, Leanheat can offer approximately 15-20MW of flexible heating power capacity during peak periods through VHS in several district heating utilities in Finland in total.

In residential buildings that roughly use 30-40% of the heating power can be easily controlled depending on the outside temperature. Energy constraints are typically not the constraining factor rather than the power. Typical concrete frame multifamily building takes approximately 10 hours to cool 1-degree, even if heating is decreased significantly, and thus typical energy capacity is 10 times the discharge power if +-0.5-degree changes in indoor temperature are allowed. To avoid additional energy consumption to customers by maintaining higher temperatures, heat losses need to be considered when production planning uses Virtual Heat Storage.

It is important to guarantee that conducting demand response does not conflict with the building owners' or residents' interests, for example in cases where the peak load component or return water temperature component is in the customer pricing models. In unbalanced heating networks, peripheral apartments might oscillate more and flexibility may need to be reduced.

6.4.1 The Vatajankoski case story

The Vatajankoski district heating utility is one of the cases where the utility has combined heating demand response to production optimization with Danfoss Leanheat®. Vatajankoski is a local, innovative energy company originally built around local hydropower in the city of Kankaanpää with 13,000 inhabitants. Vatajankoski's main businesses are energy services, construction and maintenance services, electricity transmission as well as district heating and cooling. Vatajankoski has been Danfoss' partner within Danfoss Leanheat for building-level optimization since 2018 and currently, a significant share of Kankaanpää multi-family buildings is under Leanheat building service, in which Leanheat has decreased approximately 12% of the energy consumption. In addition, peak power optimization has reduced the need for investing in new peak boiler capacity.

Vatajankoski started to operate a new waste heat plant, supplying roughly one-third of the annual heat production, combined with large conventional storage in 2021. The new production unit has increased the need for optimizing production in combination with existing bio-CHP units and gas and oil boilers. At the end of 2021, Vatajankoski and Danfoss Leanheat entered into a partnership on Leanheat Production. Before implementation, Leanheat made extensive analysis and simulations based on the production mix, analysing the possible benefits of having Leanheat Production in the combination with VHS with building-level optimization.

The goals for Vatajankoski, in combining demand forecasts with Leanheat Production, were to be able to supply precise load forecasts, robust optimization and integrate demand flexibility. A working group was established to specify the commercial process, automation and integrations. Integrations were required for automation and weather services as well as Leanheat Building. Automation was the most critical part as the production-building level integration could be solved with Leanheat VHS. Lessons learned, even more focus could have been put on daily processes, taking into consideration that there was no previous experience in production optimization. In cases where existing solutions are replaced, the focus should be more on optimization results and how to fit into the existing environment.

Production optimization and VHS were tested in Spring 2022 and the solution is now used by Vatajankoski operations and schedules through automation by their control room. Schedules have been robust and consistent and valuable results are shown compared to baseline operations without optimization. However, automatic dispatch of the systems was not established during the 2021-2022 heating season, but the aim is to have the solution running automatically in at the beginning of the heating season 2022-2023.

6.5 Leanheat learnings from the project

The following bullet points describe the biggest challenges and concerns to demonstrating CSO as well as the virtual actuation from Leanheat's perspective.

- Leanheat and Neogrid control only a very limited number of buildings in district heating networks in the HEAT 4.0 project. The low number of buildings and the fact that Leanheat is not controlling the most critical buildings in the subnetworks means that network optimization can't make decisions to, for example, decrease primary side supply temperature.
- Recruiting buildings has been slow in the project, and To reach the critical mass of buildings we would need to contact big building owners, who could supply a large set of buildings in a shorter time frame.
- Building owners were not involved as project partners, which caused some delays in the process of implementing solutions. It created as well a heavy need for anonymization in the Leanheat case. This led to challenges in implementing Leanheat solutions to both Science Cloud as well as Commercial Cloud. For future purposes, Leanheat and district heating utilities need to form a process to contact building owners.
- Simulations in Brønderslev Forsyning network showed low value for flexibility but based on Leanheat experiences, CSO can create positive benefits to district heating networks, especially in cases where there is no extensive thermal storage capacity in place. It must be noted that building flexibility can be commenced very fast when there is approval from building owners/residents, and thus Virtual Heat Storage can also be used as a short-term solution when compared to building large-scale thermal storage.
- VHS is already used in district heating networks in Finland, but minor adaptation is required for Commercial Cloud integration. In addition, the business model of Commercial Cloud still needs to be defined essentially as well as security and user handling issues before commercial setup can be established on Leanheat side. All in all, Technical Readiness Level (TRL) of the Leanheat solution is high even though CSO could not be actuated during the project period.
- Through the HEAT 4.0 project, Leanheat has increased its knowledge and understanding of the Danish district heating market and the role of building-level optimization as it differs in many ways from the other markets, for example on the value capturing side. The project has helped Leanheat to do better customer segmentation in Denmark. In future, Leanheat will put further effort into building recruitment and creating business models together with the district heating utilities to be able to recruit buildings faster and demonstrate CSO at a larger scale.

7. Cross System Optimization – Peer to Peer (CSO p2p)

The concept of the Cross System Optimization (CSO) is introduced in Section 2.1. As mentioned above, there are various possible configurations for the CSO-idea. In this work, we focus on the peer-to-peer implementation and the values that can be shown on this variation/configuration.

ENFOR lead the discussion for a high-level technical concept and was hosting workshops where various scenarios were proposed and opportunities and challenges were highlighted. By considering the demo district heating systems, but also by looking into the future heating demands and heating conditions outside Danish, the following concept and scenarios were proposed.

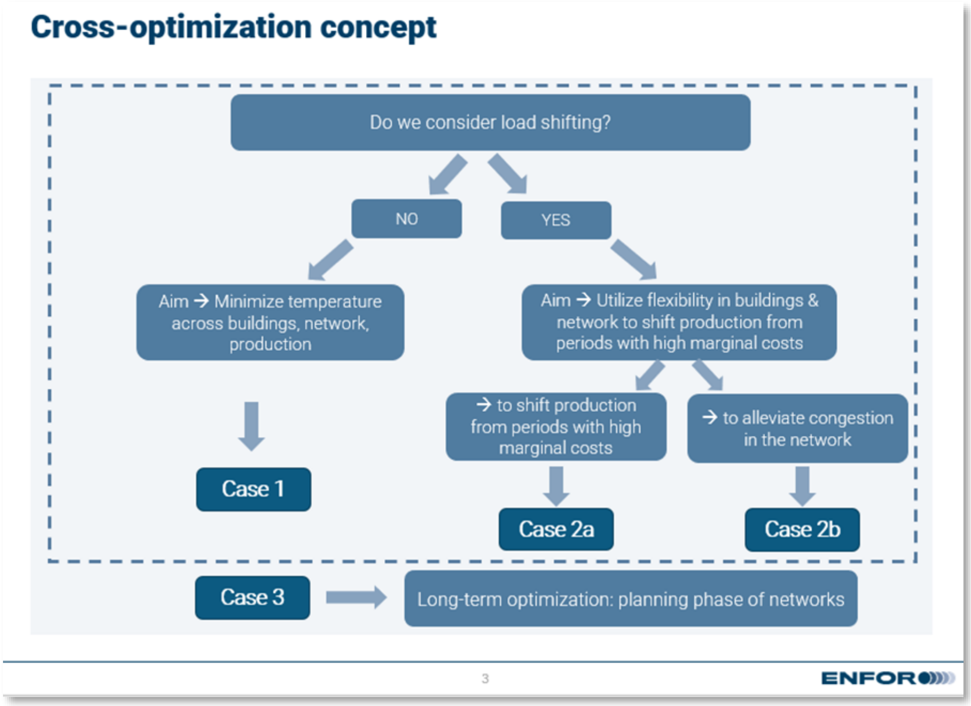

Figure 50: Schematic for cross system optimization (CSO) concept.

The optimization in the context of the project is mainly with regards to the operation stage, which should include optimization at a building, network and production level. The optimization proposed here is an economic optimization, which takes a system perspective, trying to minimize the overall costs of the system. It may be understood that is not a global optimization; each component will be a sub-optimal solution[15]. The existing tools for optimization, i.e. production optimization, network temperature optimization and building optimization will be used, exchanging information and optimizing (now informed by the optimal solutions by the others) on the same target for each scenario case.

Due to the fact, that there were not enough buildings involved to prove the effect of the ideas by HEAT 4.0 and especially the CSO concept, a simulation approach to analyse 'scenarios' is adopted here.

Two scenario strategies were proposed, with the main distinction of whether load shifting is considered or not. In the first scenario, load shifting is not considered. This is "Case 1", where the optimization tools are integrated to provide an optimized baseline, trying to minimize temperature across buildings, the network, and the production plan. In the

[15] A global optimization would demand an increased orchestration of the involved sub optimization, or even a distributed optimization approach – a work idea for the future.

second scenario, load shifting is considered, where the tools are integrated To utilize flexibility in the buildings and network. Ideally, we would like buildings to contribute to load shifting to shift the production from periods with high marginal costs (peak shaving) and to avoid congestion in the network. Given its complexity, this scenario was divided into two scenarios. The first scenario, "Case 2a" assumes that there isn't enough storage on the production side to facilitate load shifting, so the buildings are contributing to load shifting to shift production from periods with high marginal costs. The second scenario, "Case 2b", assumes that there is enough storage at the production side to cover the needs for peak shaving. Therefore, the buildings will contribute to load shifting to avoid bottlenecks in the network.

We had identified that there is a potential value in cross system optimization (CSO) with regard to long-term optimization and the planning phase of networks. But this was not within the scope of this project, and it was therefore only briefly touched upon.

The work on CSO was carried out by a working group of four companies: EMD, ENFOR, Leanheat and Neogrid. Each of them has an optimization tool:

EMD	→ production optimization
ENFOR	→ weather forecasting, heat load forecasting and temperature optimization in the distribution network
Leanheat and Neogrid	→ building optimization

Table 5: Simulation cases and scenario cases

DH cases	Hillerød Forsyning	Brønderslev Forsyning	Trefor in Kolding
Case 1	X		
Case 2a		X	
Case 2b		X	
Case 3		Not followed this path	

7.1 Case 1

Initially, the participating district heating companies identified which information should be exchanged between their tools, TO cross-optimize. After that, the companies had to establish communication between them. At this early stage of the project, the most natural and easy way to start with was Peer-to-Peer communication. The starting point was to establish communication for Case 1, as shown in the schematic of *Table 1* to Table 3.

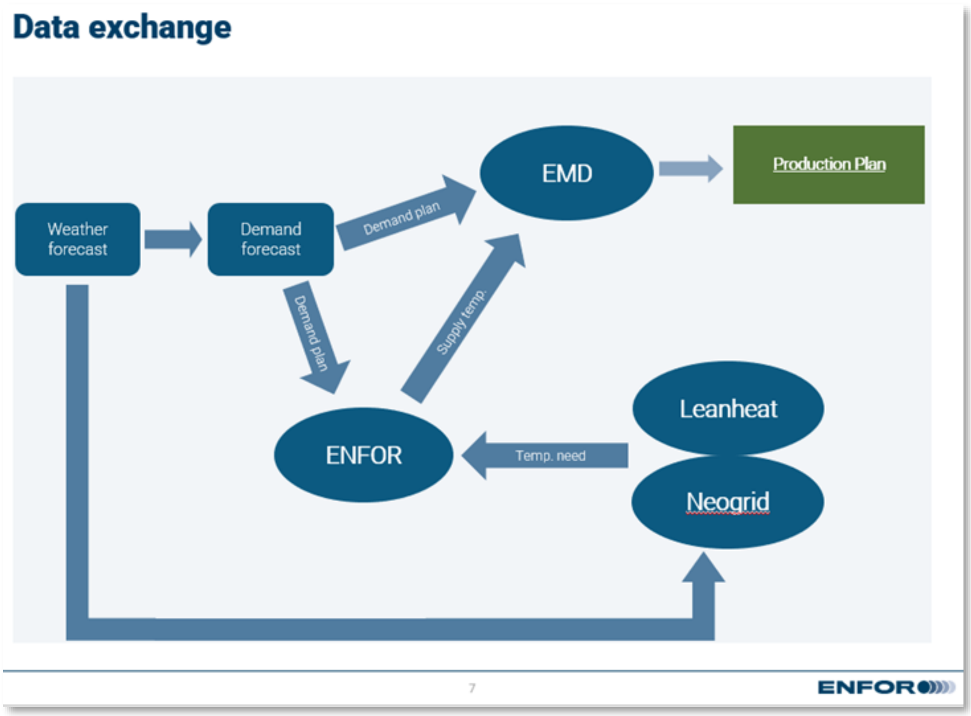

Figure 51: Case 1 - Schematic for peer-to-peer data exchange for CSO.

"Case 1" was implemented and tested for the demo district heating systems in Hillerød.

However, the real-life operation does not include the building optimization part, because not enough buildings are included in the project, i.e. controlled with a building optimization tool. For the whole distribution network to reduce its temperature, at least the critical buildings of the network should be able to reduce their temperature. Therefore, "Case 1" including building optimization was done with simulations, using real data from a participating district heating system, Brønderslev Forsyning.

7.2 Case 2a and 2b - Simulation activities for value estimation

Cases 2a and 2b, where load shifting in buildings is required, cannot be tested operationally, since not enough buildings are included in the project, as explained in the previous paragraph. Therefore, the working group decided to estimate the potential value of cross-optimization with different simulation scenarios using real data from a participating district heating system, Brønderslev Forsyning. The estimation was done with different simulation scenarios, as outlined below:

- Simulation Set 1: Value in load shifting in a district heating system
  These simulations provide the first estimations of the value in load shifting in CSO
- Simulation set 2: Estimation of yearly value in CSO based on the Brønderslev Forsyning district heating system and estimations of available flexibility
  These simulations estimate the real value of CSO with load shifting in Brønderslev Forsyning.
- Simulation set 3: Estimation of the value for temperature optimization in Brønderslev Forsyning
  These simulations estimate potential savings which could be achieved with temperature optimization in Brønderslev Forsyning – considering as well the increase of efficiency of the wood chip boiler installed at the plant.

All the simulation sets are described in the following sections below.

7.3 Simulation Set 1: Value in load shifting in the district heating system

The first simulation set focused on estimating the value of load shifting in a district heating system participating in the Day-ahead market. The simulations were performed for 1 week of operation. Periods and amounts of load shifting were chosen by EMD and do not necessarily represent the real capabilities of the system. The reason for performing the simulations was to discover whether any value could be observed in CSO in a system similar to Brønderslev Forsyning, which is equipped with a large heat storage tank. To make it very clear to the readers, the values to be gained by thermal storage, network and buildings compete on the same potential. Amongst other, this is discussed later in this section.

The simulations were performed with a simplified Brønderslev Forsyning model, were the distribution of demand around different areas of the city was disregarded for simplicity. The generation plant was modelled as shown in Figure 52.

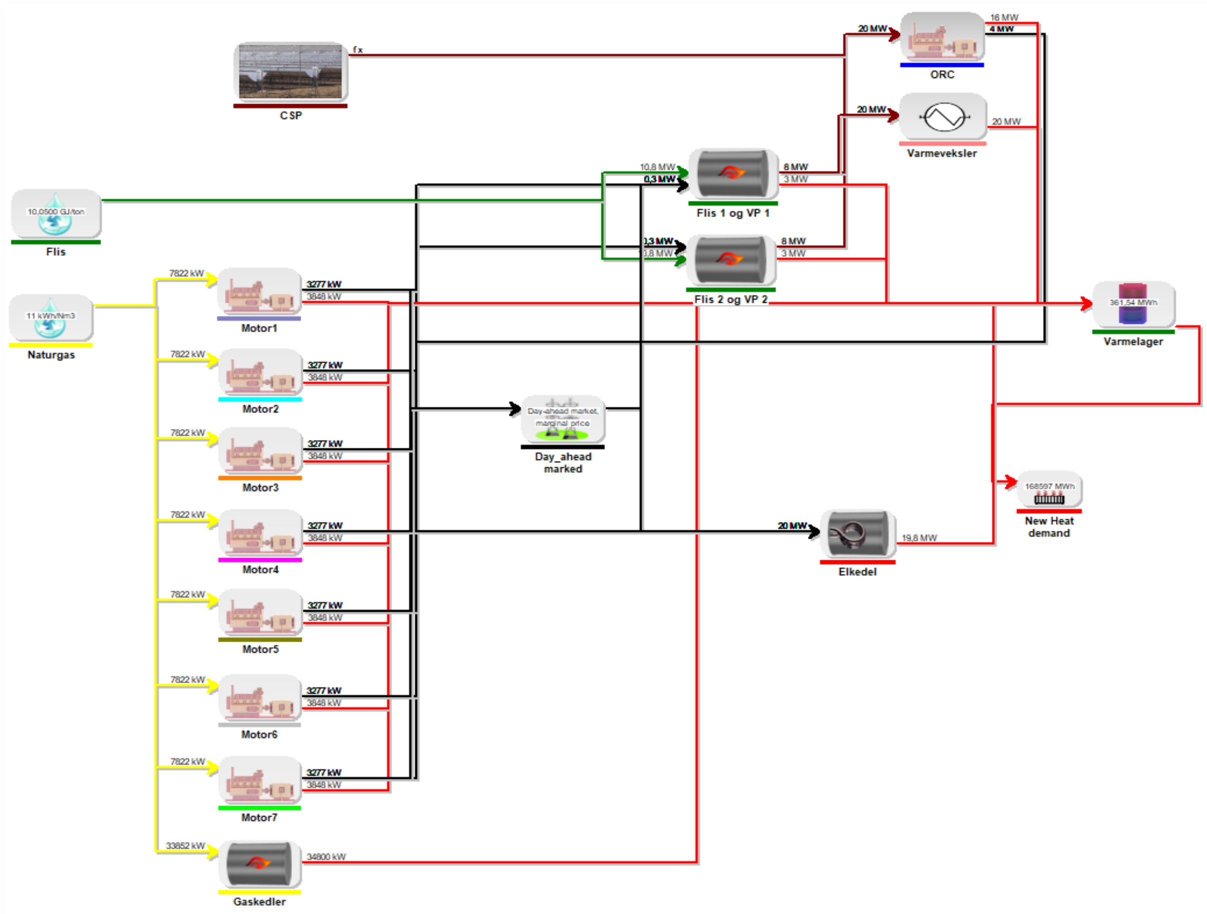

Figure 52: Generation plant used in Simulation set 1 for estimation of CSO value.

7.3.1 General estimation of the value in load shifting

The first simulations were done in an unrestricted system, where load shifting could contribute to more flexibility of the system. The first completed simulated week was a week in February, where the operation income without load shifting was calculated to be -0.272 M DKK. The details of the optimized operation during the simulated week can be seen in Figure 53. Heat production from a natural gas-fired boiler is marked in orange. This operation is needed because the prices on the day-ahead market are low during these hours and the heat storage is empty. Hence, there is a potential for a positive gain from load shifting. If the heat demand during these hours could be shifted forward to the period with good day-ahead prices, there is a potential for reduced operation cost of the plant. 36.6 MWh load shifting forward was simulated and the results is shown in Figure 53. The operation income after load shifting is – 0.270 M DKK. Hence, the savings are 2204 DKK ≈ 61 DKK/MWh shifted in one chosen week.

Figure 53: Optimal operation of the system in a week in February without load shifting; marked in orange is heat production from a gas boiler, which could be avoided with load shifting.

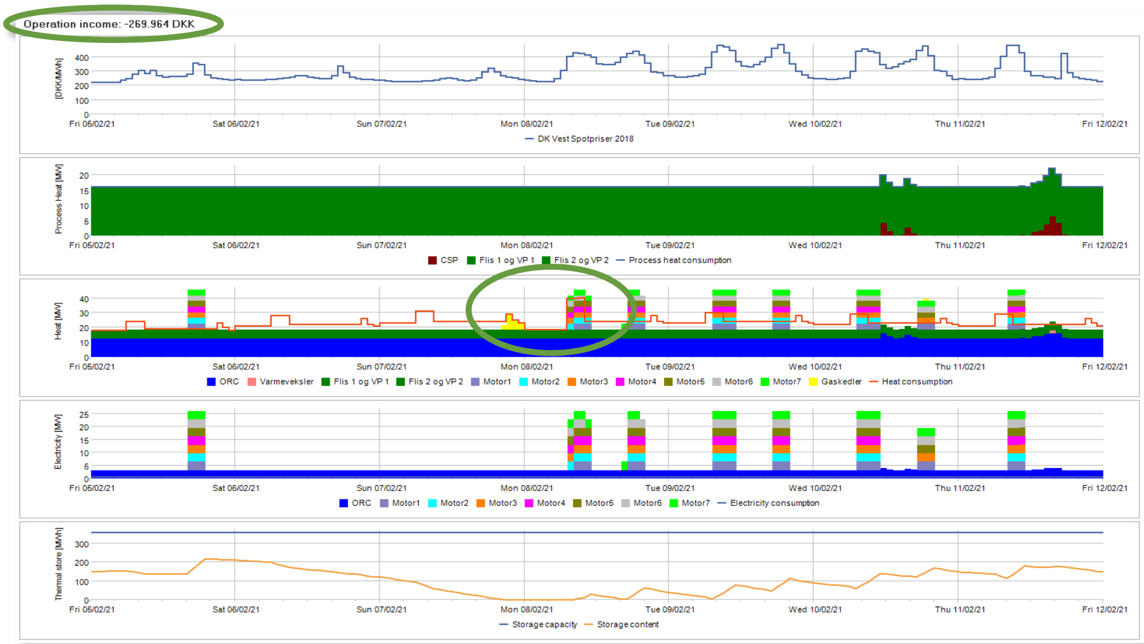

Figure 54: Optimal operation of the system in a week in February with 36.4 MWh load shifting forward; marked in green is the shifted load, which results in reduced time of natural gas fired boiler operation.

Another week in January was simulated with the same approach. The operation income without load shifting for this week is -0.691 M DKK. The optimal operation is shown in Figure 55, and the period, where a potential for load shift was found, is marked in orange. 70 MWh load shifting forward was simulated and the result is presented in Figure 56. This significant load shift did not result in any savings because in this case, it resulted only in the shift of the natural gas operation.

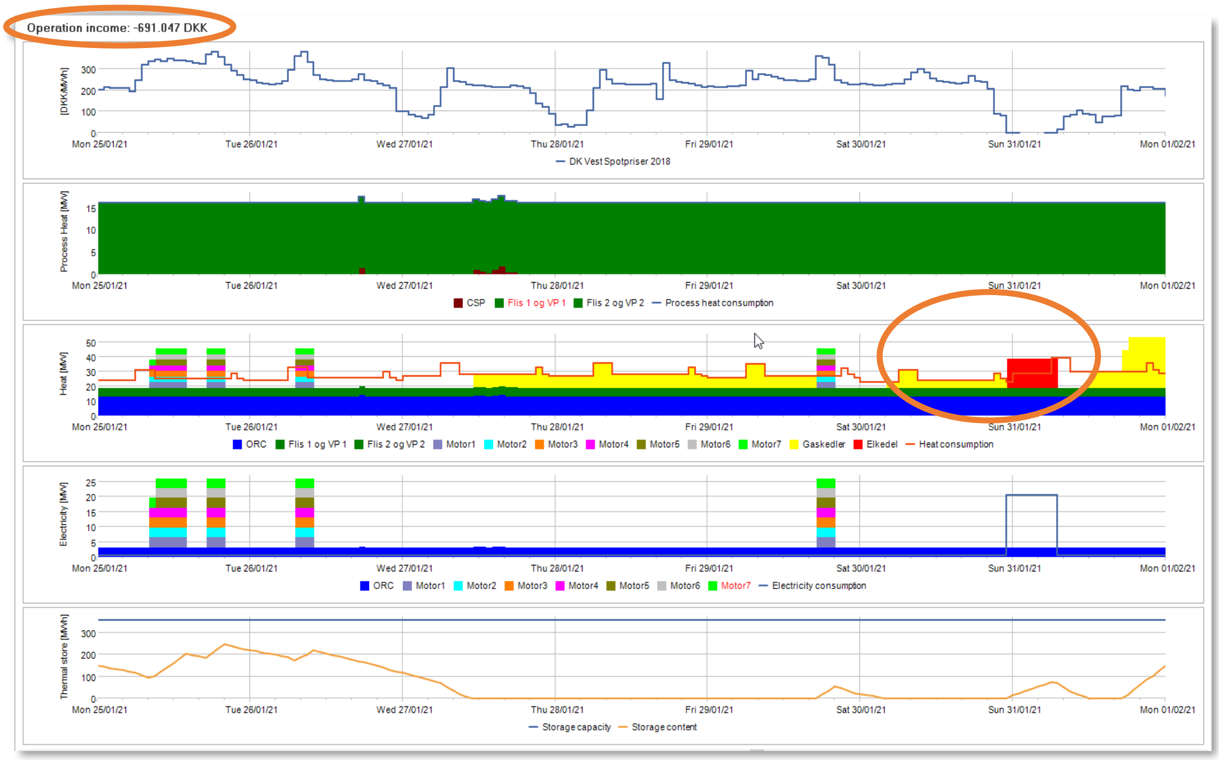

Figure 55: Optimal operation of the system in a week in January without load shifting; marked in orange is heat production from a gas boiler, which could be avoided with load shifting.

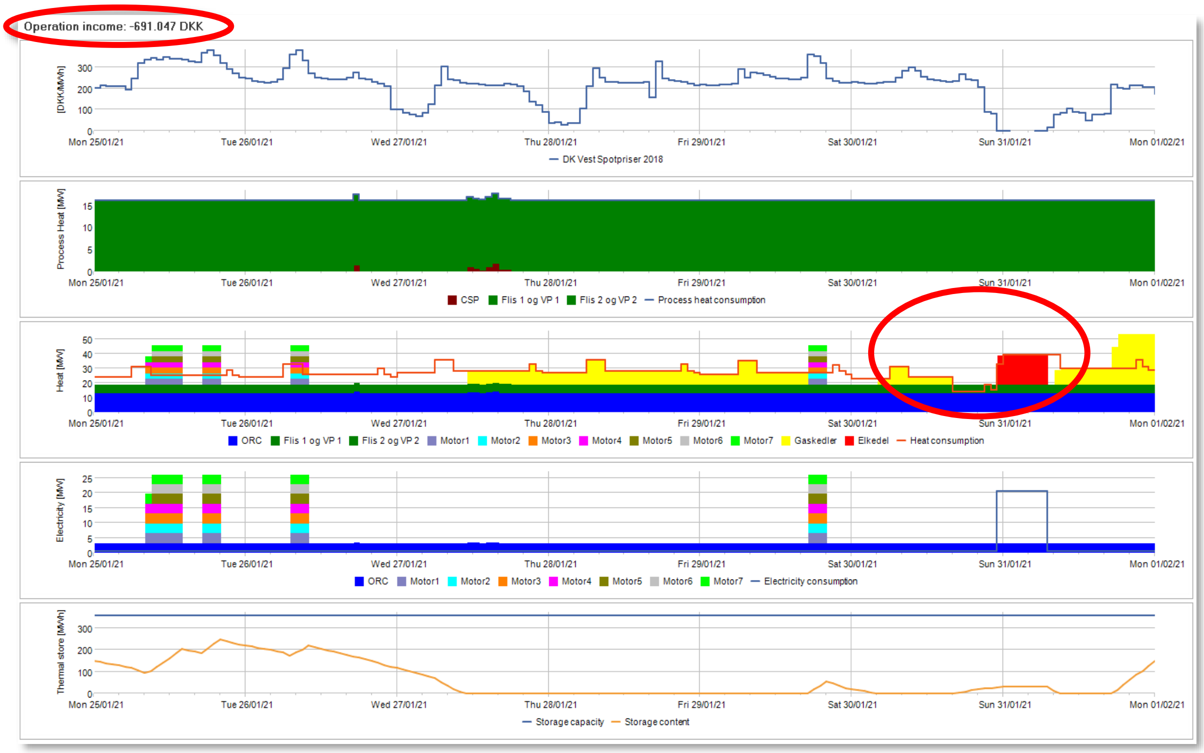

Figure 56: Optimal operation of the system in a week in January with 70 MWh load shifting forward; marked in red is the shifted load, which results in a reduced time of natural gas-fired boiler operation.

These two simulations show the challenge behind finding the good periods where load shifting can result in a significant gain. The two load shifts were done at a similar moment to avoid using the natural gas boiler and when the storage was empty, but whereas the first load shift resulted in economic savings, the second did not. For this reason, when implementing flexibility in the system, the simulation of the production optimization should be done for multiple scenarios To prove that the available flexibility will result in financial improvement.

7.3.2 Estimation of value in load shifting for peak shaving

The second simulations were done with an additional constraint introduced in the system – transmission constraint from the generation to the demand. The schematic of the system is shown in Figure 57. This was done to estimate the possible advantage of load shifting in CSO for peak shaving. The capacity of transmission was set to 18 MW. In the reference calculation, any demand exciting 18 MW was covered by the peak boiler installed in the demand area. The heat demand and the source of heat are shown on the graph in Figure 58.

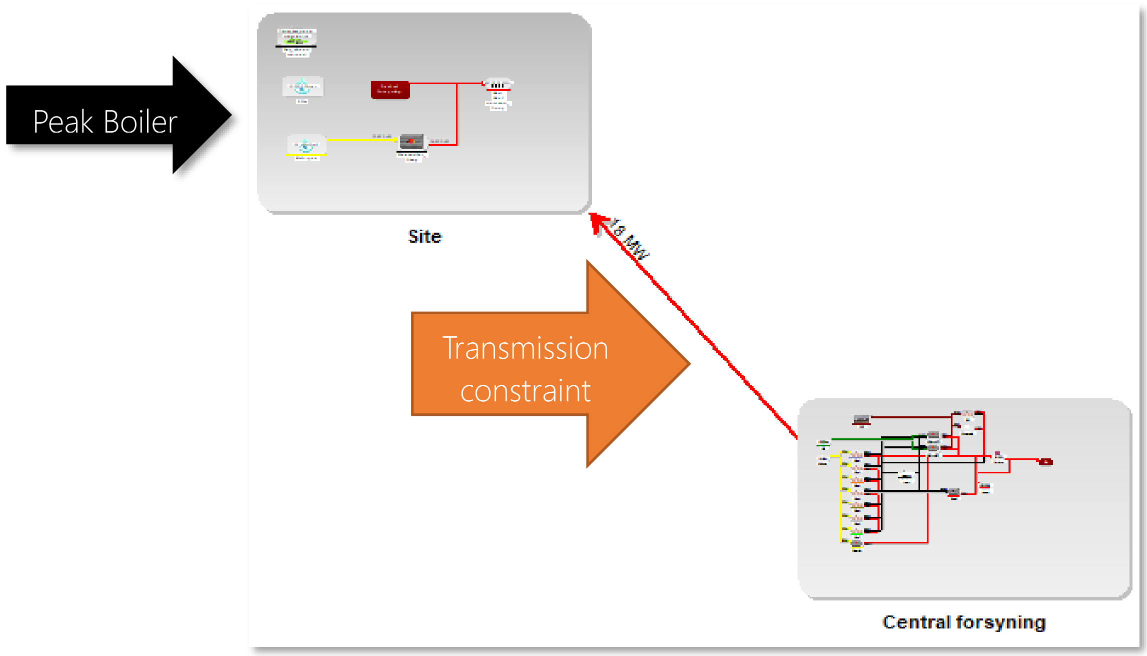

Figure 57: Schematic of the system with introduced transmission constraint.

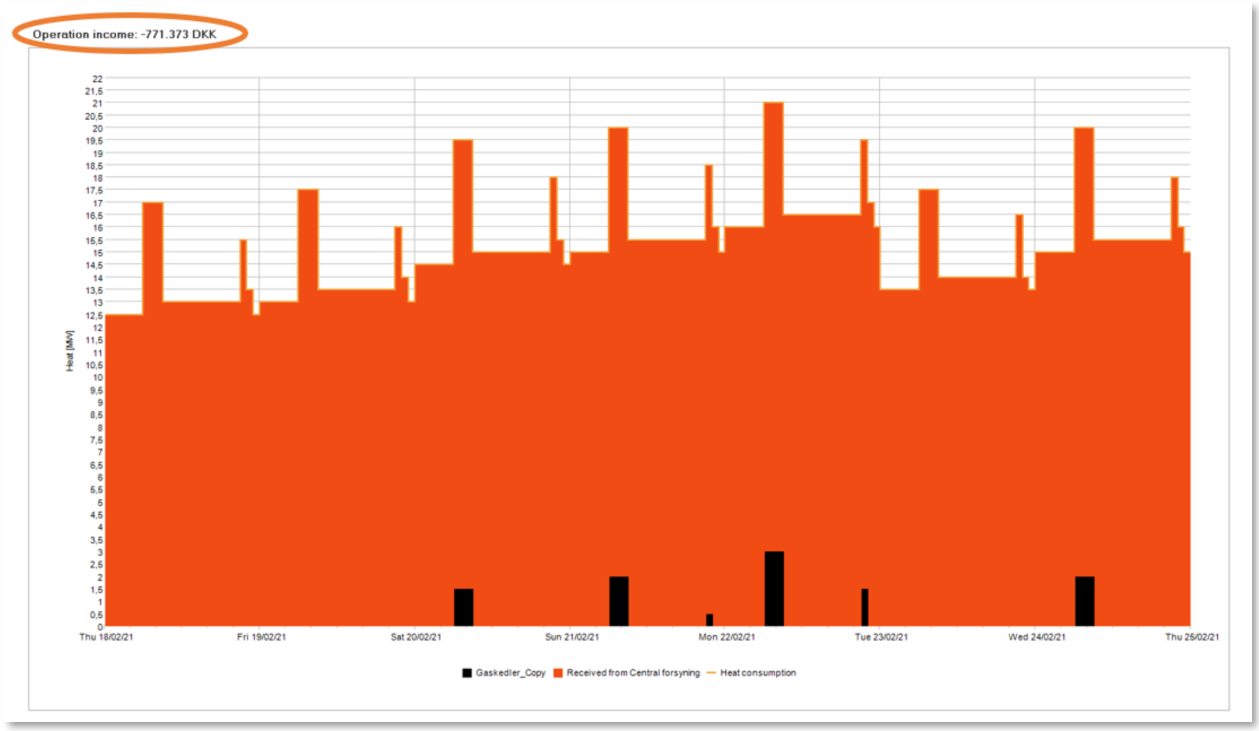

Figure 58: Heat demand and the source of heat for covering the demand; orange - covered by the central plant, black - covered by the peak boiler.

The peak boiler needs to be turned on multiple times during the week of operation without load shifting. The operation income in that week is -0.771 M DKK. 27.5 MWh load shifting for peak shaving was simulated and the operation income during the week is -0.770 DKK. Hence the savings are 1569 DKK ≈ 57 DKK/MWh shifted.

As we see in Figure 59 compared to the previous Figure 58 scenario, the local gas boilers are not taken into use and hence all demand heat is covered by the central plant.

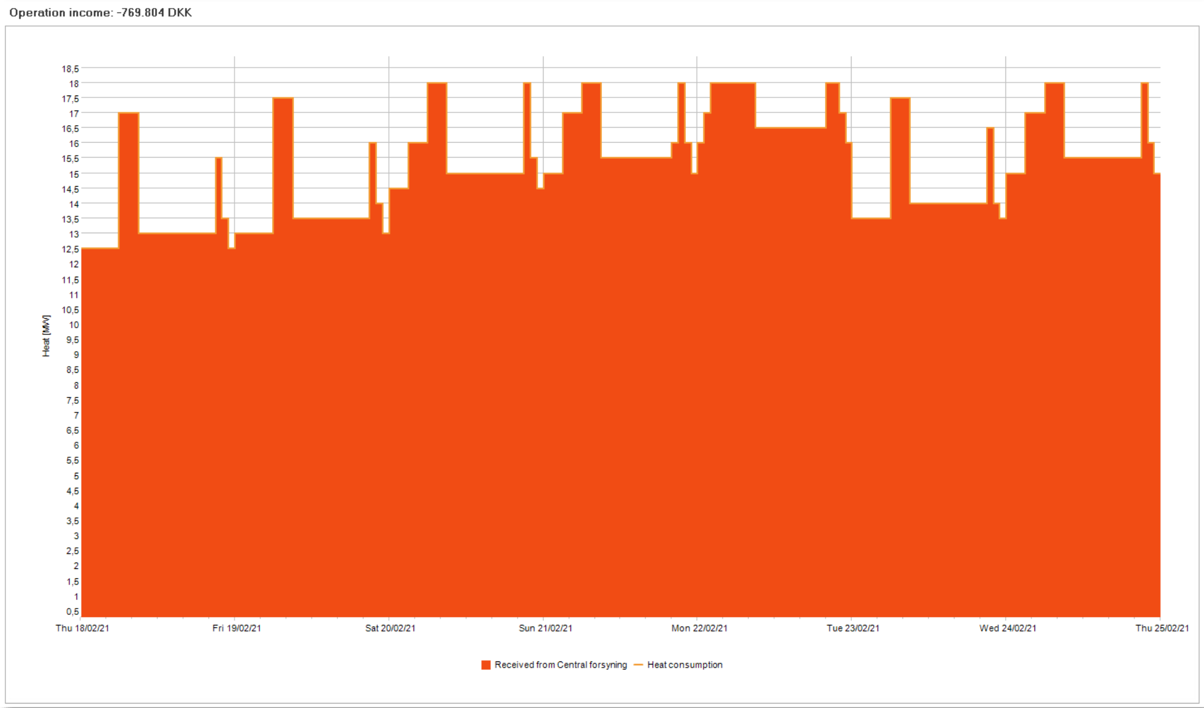

Figure 59: Heat demand and the source of heat for covering the demand; orange - covered by the central plant, black - covered by the peak boiler.

7.3.3 Estimation of value in load shifting without heat storage

The third simulation was performed with the assumption that there is no heat storage in the system. One week was simulated and the possible gain was estimated. In the reference case without load shifting, the operation income is -0.808 M DKK. The optimal operation and period identified for load shifting are shown in Figure 60. 45 MWh back-wards load shifting was simulated, and the results are shown in Figure 61. The load shift allowed for more electricity generation during the period with high electricity prices on the day-ahead market. The operation income with load shifting is -0.803 M DKK. Hence the savings are 4607 DKK ≈ 102 DKK/MWh shifted.

The potential gain from load shifting in systems without heat storage is higher because the effects of the storage are distributed as a potential for other flexibility services. It is also easier to determine periods where gain will be obtained. This is an important discovery for systems which are not equipped with heat storage, where the result will be a real gain from load shifting based on CSO.

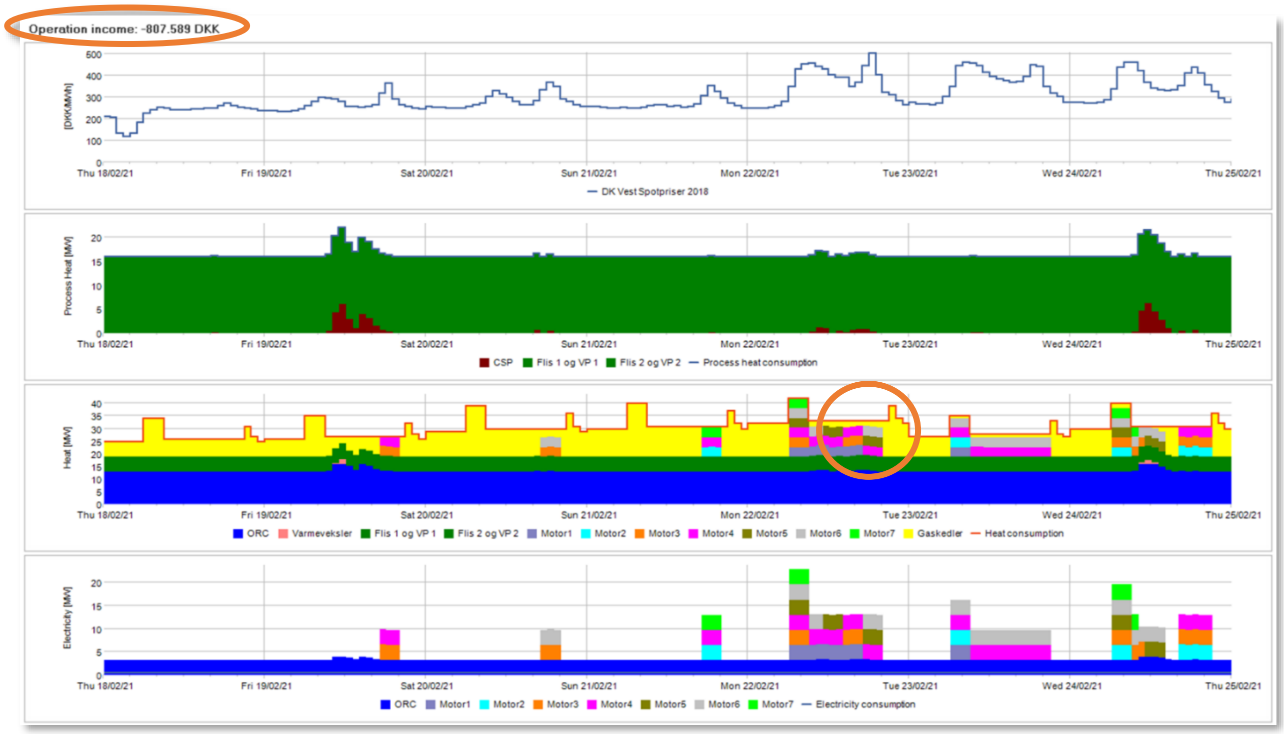

Figure 60: Optimal operation of the system without heat storage, in a week in February without load shifting; marked in orange is heat produc-tion from a gas boiler, which could be avoided with load shifting.

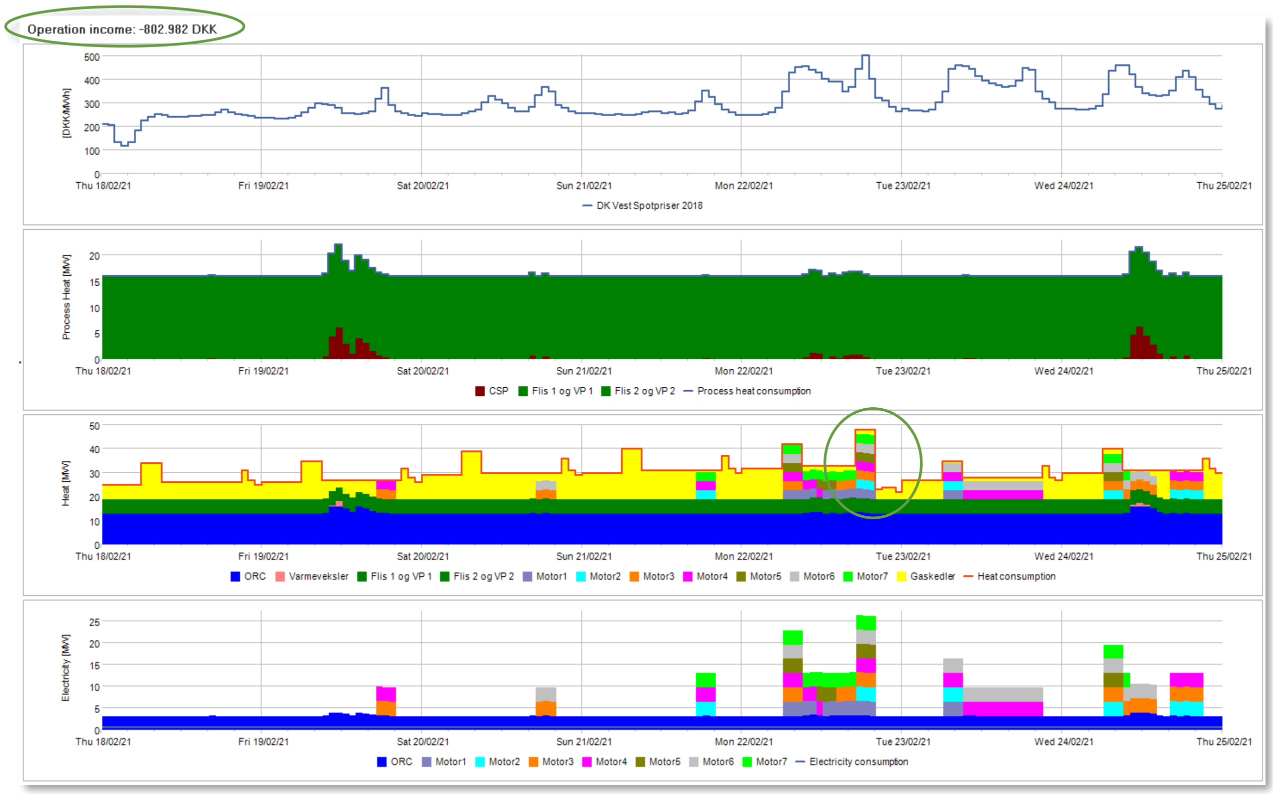

Figure 61: Optimal operation of the system without heat storage, in a week in February with 45MWh load shifting; marked in green is the load shifted backwards, which results in increased gas engines production during a period with high day-ahead prices.

7.4 Simulation set 2: Estimation of annual gain from CSO and flexibility

The second simulation set focused on simulating the existing Brønderslev Forsyning district heating system. The value of CSO optimization in a year of operation was estimated. It was done based on inputs from the partners – ENFOR, Neogrid and Leanheat - concerning available flexibility. The available flexibilities were incorporated into the model as additional storage included locally at each of the areas in Brønderslev. The storages have a maximum capacity and maximum charging and discharging power. The resulting energyPRO model is shown in Figure 62.

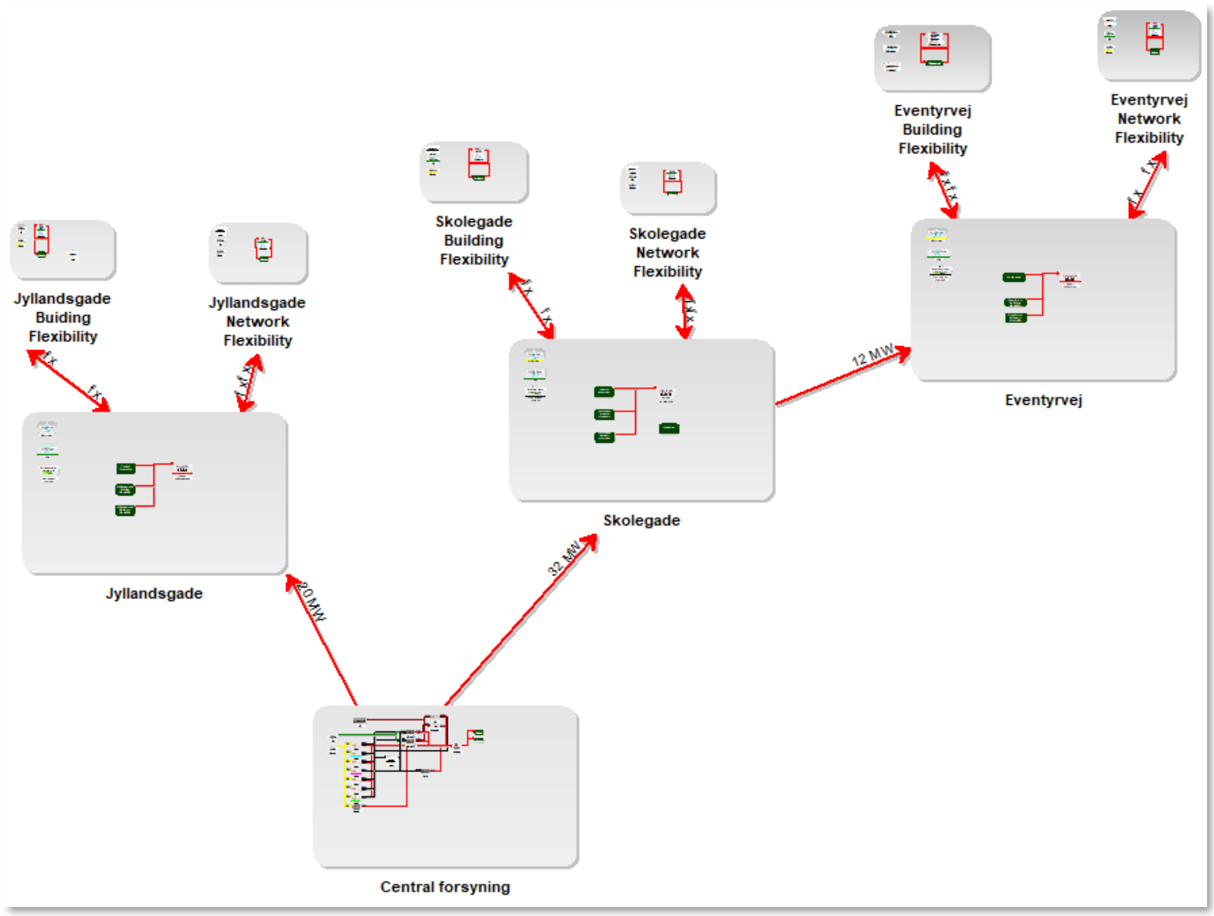

Figure 62: energyPRO model used in the CSO value over a year of operation in Brønderslev Forsyning.

The parameters of building and network flexibility for different areas of the city are summarized in *Table 6* and *Table 7* respectively. The resulting capacity of the storage added to the model to simulate building and network flexibility is shown in Figure 64 and Figure 65.

7.4.1 Approach for estimating network flexibility

The flexibility power (P_flex) for the distribution network was estimated as time series, based on historical data of the flow time series, and by assuming an allowed temperature increase (the water inside the distribution pipes can be charged), in hourly resolution, for each of the sub-networks. The power depends on the ΔT that is assumed to be added to the water temperature (P_flex*ΔT). The suggested/initial temperature increase was ΔT=2 °C.

To estimate the storage capacities, a representative flow for each of the sub-networks was selected and the resulting time delay was estimated. The same allowed ΔT was used as in the P_flex time series.

7.4.2 Approach for estimating building flexibility

The methodology for estimating the building flexibility was based upon a simplified model of the energy demand. The hourly heat demand was fitted with a simple degree-day model, using the total demand of the pool:

P(t) = a * min(daily average ambient temperature, T_balance) + b

The a, b and T balance are fitted on the data for the aggregate of buildings, which were obtained from ENFOR.

As a result, a simple storage model was built with an energy capacity and maximum charge/discharge rate (power flexibility). Based on experience, the available power flexibility was estimated to be P(t)/4 and the energy available was set to 3h of that amount of power released continuously.

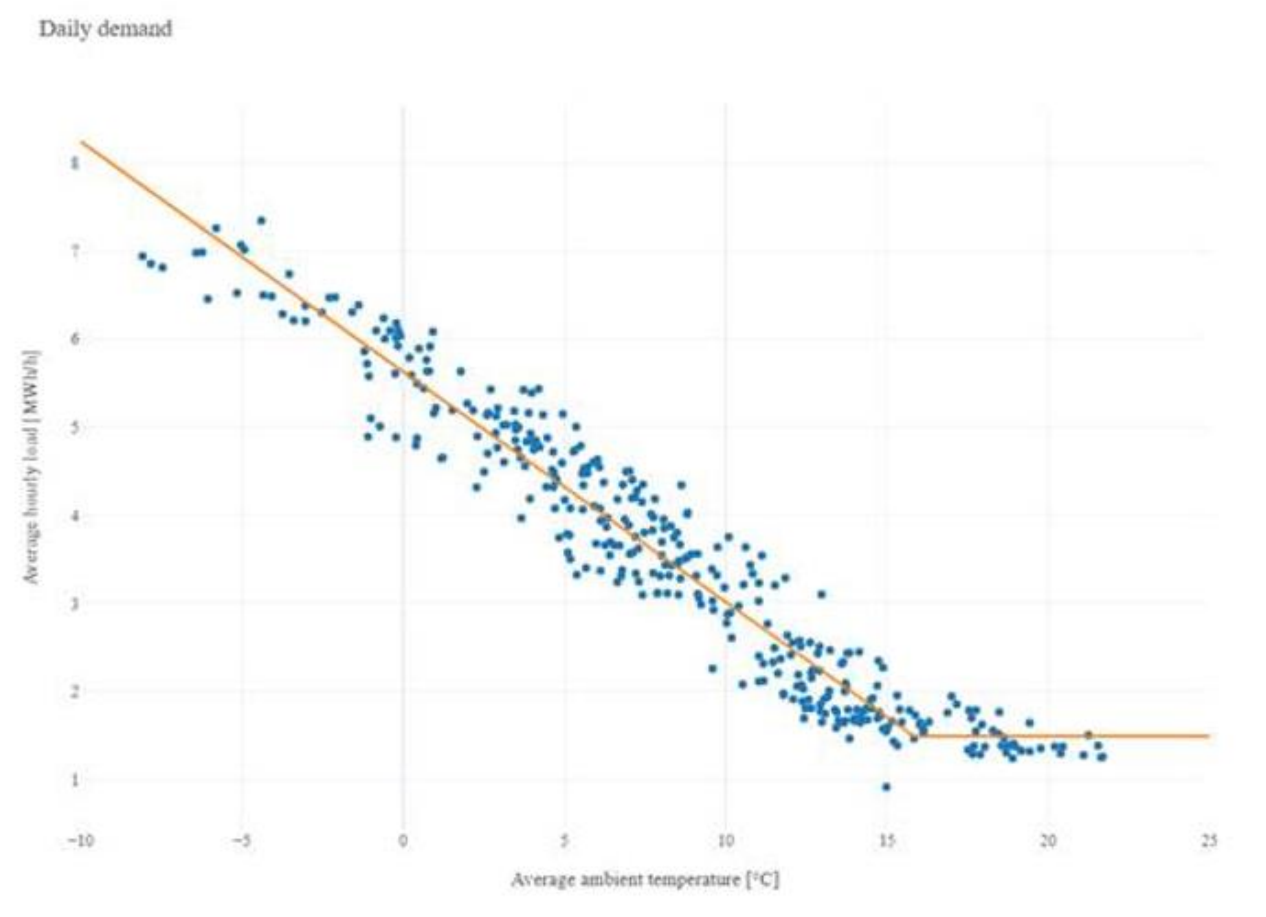

Figure 63: Daily energy demand profile for the Eventyrvej subnet in Brønderslev Forsyning (based upon data from ENFOR).

Remark: It is important to note, that only one single subnetwork (Eventyrvej) was used to build a model upon, while EMD simulated the production of the system as a whole. When looking at system level, the actual flexibility of the buildings in the whole of the city would therefore be quite higher.

Table 6 Parameters used in modelling of building flexibility.

Buildings	Charging Power (P_flex)	Max Storage Content
Eventyrvej	0.37+0.065*max((15.8-T_amb),0)	3*P_flex
Skolegade	0.48+0.13*max((15.1-T_amb),0)	3*P_flex
Jyllandsgade	0.49+0.10*max((15.3-T_amb),0)	3*P_flex

Table 7 Parameters used in modelling of network flexibility.

Network	Charging Power (P_flex)	Max Storage Content
Eventyrvej	Time Series*ΔT	0.228*ΔT
Skolegade	Time Series*ΔT	0.587*ΔT
Jyllandsgade	Time Series*ΔT	0.532*ΔT

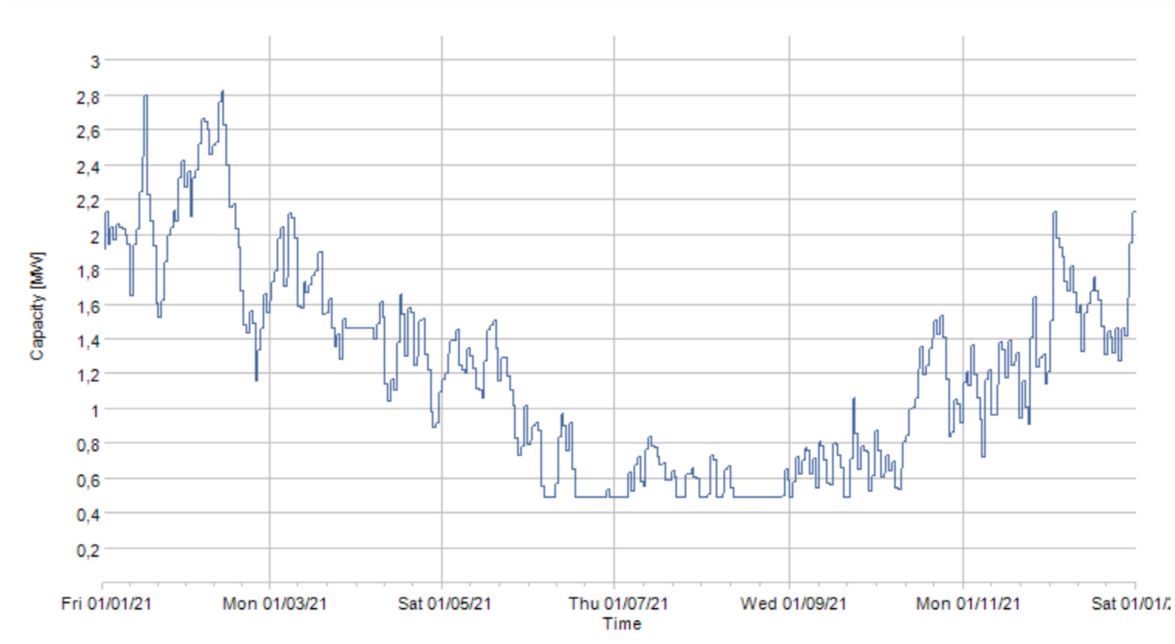

Figure 64: Capacity of the storage simulating available building flexibility over a year.

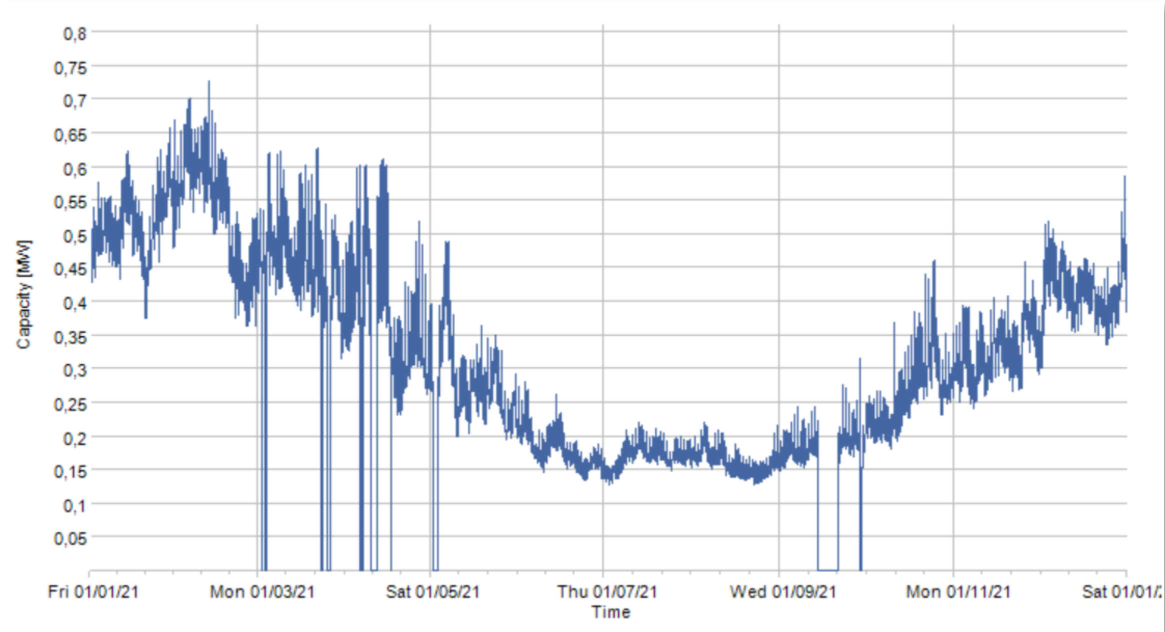

Figure 65 Capacity of the storage simulating available network flexibility over a year.

To estimate the potential of flexibility from CSO, the following simulations were performed:

1. Simulation without flexibility
2. Simulation with buildings flexibility enabled
3. Simulation with network flexibility enabled
4. Simulation with both flexibilities enabled
5. Simulation without flexibility and without heat storage
6. Simulation with network flexibility and without heat storage
7. Simulation without flexibility and transmission constraint to Eventyrvej
8. Simulation with building and network flexibility enabled and transmission constraint to Eventyrvej

All of the simulations were performed with the Brønderslev model and the optimization period was 1 year.

The results of simulations 1-4 are summarized in *Table 8*. The savings over a year of operation with building flexibility enabled are 3825 DKK, with network flexibility 1868 DKK and with both flexibilities 4520 DKK. The savings per MWh shifted are also lower. The more flexibility incorporated into the system the lower the savings can be seen. This is because, during the hours, where flexibility is most advantageous, the savings may already be captured with the low flexibility from the network. These are low values considering the total operation costs of Brønderslev Forsyning.

The main reason is the already existing flexibility from big heat storage, which allows gaining from increased production when electricity prices are favourable. The second reason is that the capacity of flexibility from buildings and network is low compared to the heat demand. The estimations performed in the previous chapter was considering much higher load shifts. The total amounts of used flexibility over a year are summarized in *Table 9*. These figures are low compared to the total demand and previously calculated gains from load shifting, where we talked about shifting around 40-50 MWh in several hours.

Table 8 Results of simulations 1-4, savings from enabled flexibility over a year of operation

	Without flexibility	With building flexibility	With network flexibility	With both flexibilities
Savings over a year [DKK]	0	3825	1868	4520
Savings per MWh shifted [DKK]	-	17.4	28.1	15.7

Table 9 Used flexibility over a year of operation

Flexibility used when Building Flexibility included [MWh]	
Buildings Eventyrvej	57.3
Buildings Jyllandsgade	78.1
Buildings Skolegade	83.9
Network Eventyrvej	0
Network Jyllandsgade	0
Network Skolegade	0
Sum	**219.3**

Flexibility used when Network Flexibility included [MWh]	
Buildings Eventyrvej	0
Buildings Jyllandsgade	0
Buildings Skolegade	0
Network Eventyrvej	11.4
Network Jyllandsgade	29.3
Network Skolegade	25.8
Sum	**66.5**

Flexibility used when Both Flexibility included [MWh]	
Buildings Eventyrvej	56.5
Buildings Jyllandsgade	74.6
Buildings Skolegade	83.4
Network Eventyrvej	13.2
Network Jyllandsgade	31.9
Network Skolegade	28.9
Sum	**288,5**

The results of simulations 5 and 6 are summarized in *Table 10*. In simulation without heat storage in the system, the gain from only network flexibility, which is smaller compared to the available building flexibility, was calculated to be 0.775 M DKK. Which is much more significant compared to the results of simulation 1-4. The savings per MWh are also significantly increased compared to the previous simulations: 444.3 DKK/MWh shifted. That indicates that flexibility from CSO should be taken into consideration in district heating systems not equipped with a heat storage and as an alternative in design of new district heating systems. The increased value is a consequence of increased usage of the flexibility.

As shown in *Table 11*, the storage was utilized for short periods to store 1744 MWh of heat over the year. Compared to the simulation with heat storage and network flexibility, where 66 MWh were stored over a year, this is an increase of around 1700 MWh.

Table 10 Results of simulations 5 and 6, gain from flexibility over a year of operation, simulation without heat storage.

	Without flexibility	With network flexibility
Savings [DKK]	0	0.775 M
Savings per MWh shifted [DKK]	-	444.3

Table 11 Used flexibility over a year of operation, simulation without heat storage.

	Flexibility used when Network Flexibility included [MWh]
Buildings Eventyrvej	0
Buildings Jyllandsgade	0
Buildings Skolegade	0
Network Eventyrvej	364,8
Network Jyllandsgade	703,3
Network Skolegade	676,5
Sum	**1744,6**

The last two simulations 7 and 8 were performed with a transmission constraint introduced between the main plant and one of the areas of Brønderslev's district heating network – Eventyrvej. - see a schematic of the simulated system in Figure 66. The transmission to Eventyrvej has a capacity of 5.8 MW and a peak boiler is introduced at Eventyrvej. Simulation 7 was done without flexibility in the system and simulation 8 with only Eventyrvej flexibility enabled – both buildings and network flexibility included. The gain from enabled flexibility over a year of operation was calculated to be 9639 DKK. The difference between demand-supply in Eventyrvej with and without flexibility from CSO enabled can be seen comparing Figure 67 and Figure 68.

Figure 67 shows the situation when the flexibility is not enabled, the demand is covered by heat delivered from the central plant and the peak boiler whenever the transmission capacity limit is reached. In Figure 68 we see the situation with enabled flexibility. When the demand exceeds the transmission capacity by a small amount and the network and buildings can be preheated, the demand is covered by flexibility. However, if the demand is exceeding the transmission capacity for a long time and there is no possibility to preheat the buildings and network, the peak boiler needs to be in operation. This shows the advantages and disadvantages of CSO-enabled flexibility. In a time where the transmission capacity is rarely exceeded, CSO flexibility is very valuable.

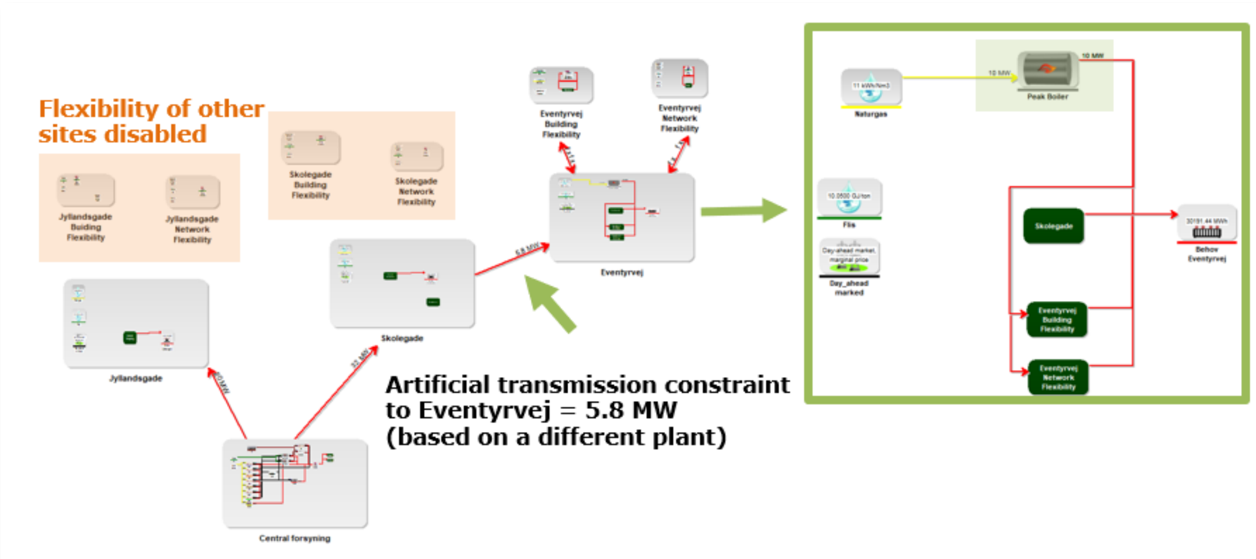

Figure 66: Schematic of system simulated with an artificial transmission constraint between Skolegade and Eventyrvej in Brønderslev.

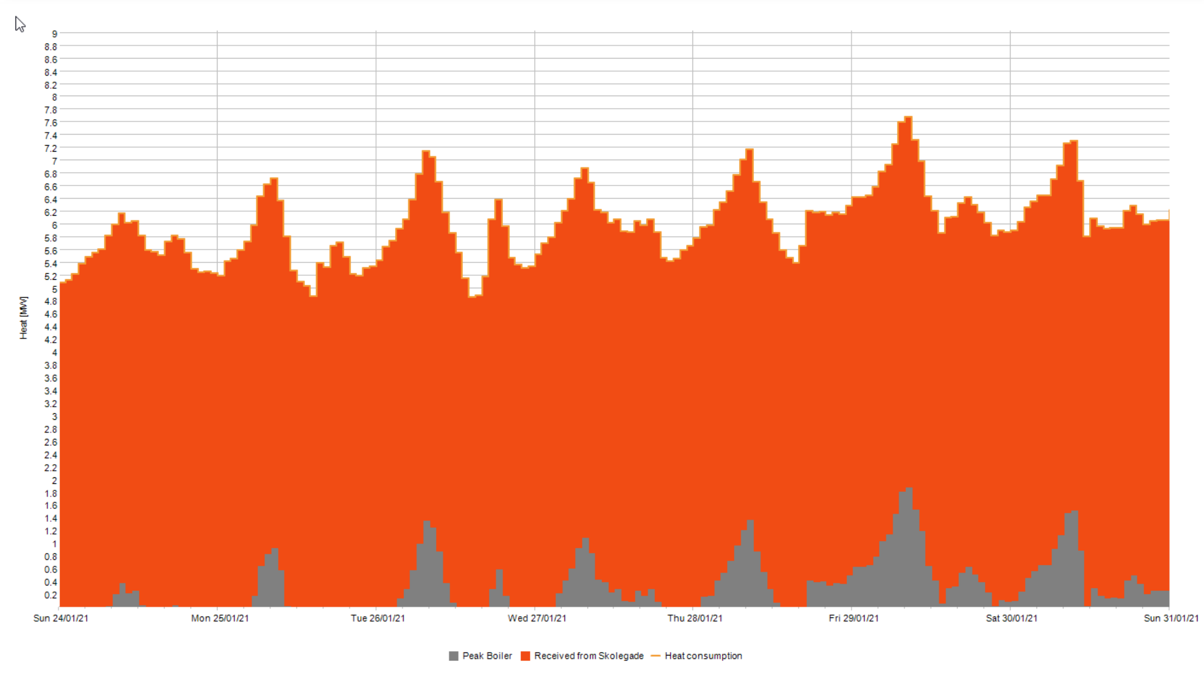

Figure 67: Heat demand supply source in Eventyrvej - no flexibility; orange – heat delivered by the central plant, grey – heat produced by the peak boiler.

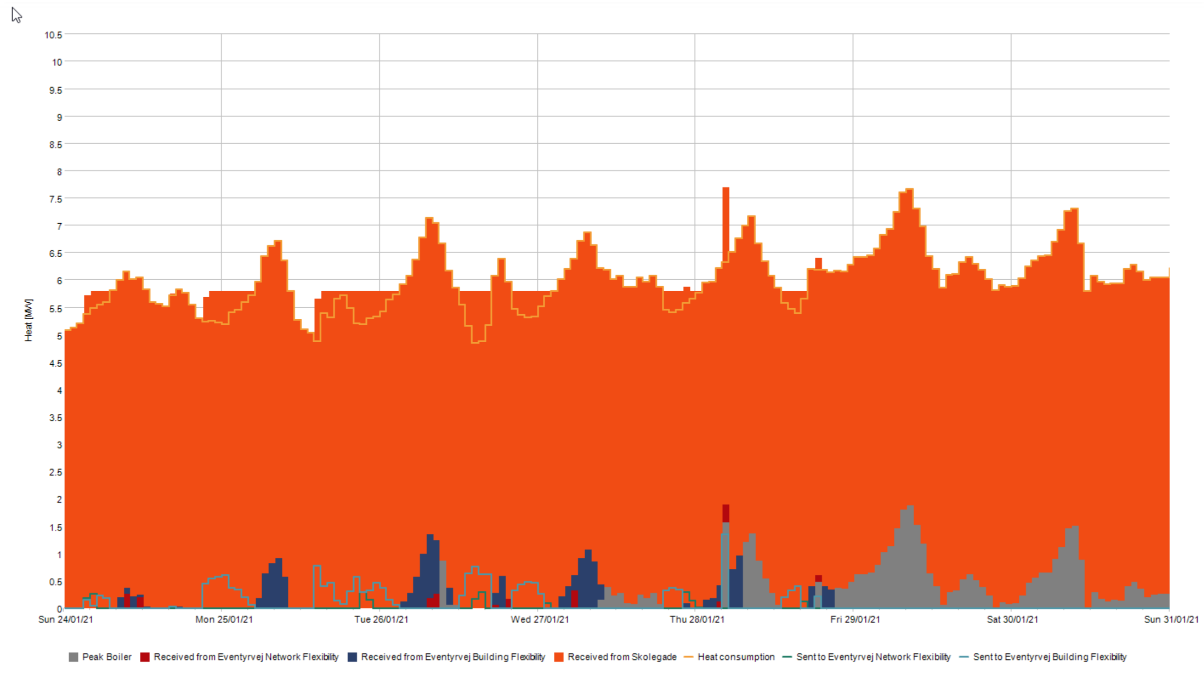

Figure 68: Heat demand supply source in Eventyrvej - with flexibility; orange – heat delivered by the central plant, grey – heat produced by the peak boiler, dark blue – building flexibility, red – network flexibility.

7.5 Simulation set 3: Estimation of the value of temperature optimization in Brønderslev Forsyning's network

The last set of simulations focuses on estimating the value of temperature optimization in a Brønderslev Forsyning distribution system. The simulations were done with representative supply and return temperatures for a year of operation. The maximum possible reduction of supply and return temperatures were assumed to be 5°C, with a limitation that the supply and return temperatures cannot come under 60°C and 30°C. Two possible savings were identified:

1. Efficiency gain from the wood chip boiler due to lower condensation temperature. Based on a previous project the gain was assumed to be 1%/5°C.
2. Reduction of heat loss in the network.

Simulations were performed to quantify the effect of both savings and the results are summarized in *Table 12*. The savings from both situations resulted in savings of 548036 DKK over a year of operation.

Table 12 Estimation of savings from temperature optimization in Brønderslev Forsyning's network.

	Reference	With efficiency gain	With heat loss reduction	With heat loss reduction and efficiency increase
Savings [DKK]	0	0.299 M	0.253 M	0.548 M

7.6 Possible value from CSO in markets other than Day-ahead market

As presented in the above sections, the value of CSO in Day-ahead market is limited, if big heat storage is present in the district heating system. This is the usual case at most of the Danish district heating plants.

The value of CSO could be increased if markets other than Day-ahead market are considered, see the list in *Table 13*.

Table 13: Danish electricity markets.

Marked	Gate closure	Organisering	Prisafregning
Frekvensregulering Frequency containment reserves (FCR)	8.00 the day before	Minimum 1 MW symmetric up/down Divided into four-hour blocks Bloc 1: Kl. 00.00 - 04.00 Bloc 2: Kl. 04.00 - 08.00 Bloc 3: Kl. 08.00 - 12.00 Bloc 4: Kl. 12.00 - 16.00 Bloc 5: Kl. 16.00 - 20.00 Bloc 6: Kl. 20.00 - 24.00	Marginal price
Rådighed i regulerkraftmarkedet manual Frequency Restoration Reserves (mFRR)	9.00 the day before	Bids for each of the 24 hours tomorrow. Asymmetric bids.	Marginal price
Spotmarkedet Day ahead wholesale market	12.00 the day before	Bids for each of the 24 hours tomorrow. Asymmetric bids. Price independent, price dependent or bloc bids.	Marginal price
Aktivering i regulerkraftmarkedet Replacement Reserves (RR)	45 minutes before the operating hour	Bid for the next hour. Asymmetric bids.	Marginal price
Aktivering i specialregulering	45 minutes before the operating hour	Bid for the next hour. Asymmetric bids.	PayAsBid
Elbas Intraday wholesale market (ID)	45 minutes before the operating hour	Bid for the next hour. Asymmetric bids.	PayAsBid

If e.g. intraday market is considered, we may analyse the situation shown in *Table 13: Danish electricity markets.* Table 13. In a normal operation on the intraday market, we have the following workflow:

- As a starting point, the won sale in the Day Ahead market will fill the thermal storage in Brønderslev Forsyning at this hour and Intra Day sale is thus not possible at this hour.
- Downward regulation will be offered in the Regulating Power market (RR) in the hours before to make room in the storage, making Intra Day sales possible at this hour.

However, Cross System Optimization offers another opportunity for Intra Day sales at this hour:

- A request is sent from the plant tool to the building tool asking for advancing the heat demands to be made hours before.
- If this is possible, the building tool will send a new prognosis to the grid tool, which will create a demand prognosis (amounts and temperatures) to be sent to the plant tool.
- The plant tool will calculate how much sale is thus possible in this hour and calculate the marginal price for this sale, and the information will be sent to the Balancing Responsible Party, which can start trading this hour in Intra Day market.

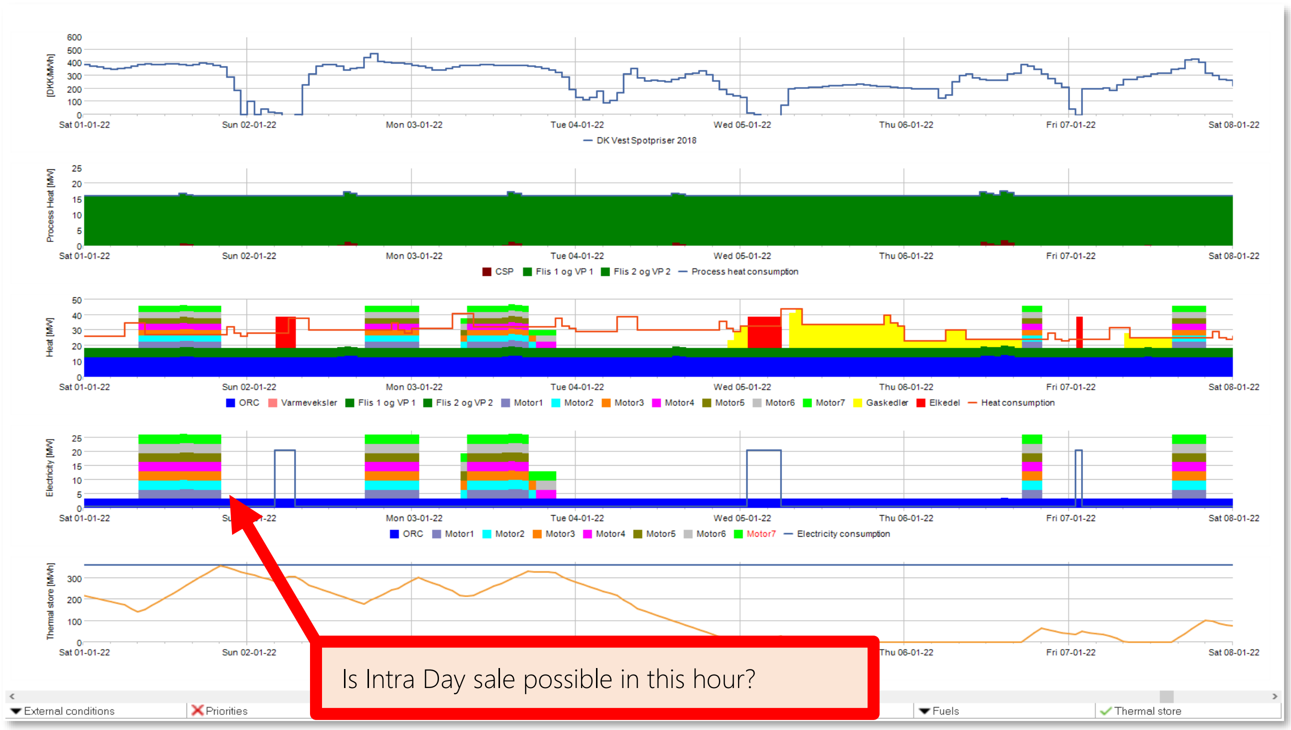

Figure 69: An example of a building scenario in Brønderslev Forsyning - for making an intraday sale possible.

7.7 Lessons learned from simulations by EMD

The simulations performed in this chapter focused only on the production optimization and potential cost reduction within that area. The quantified savings are based on simulations, hence there is a potential for additional savings in a real system.

The overall conclusions from the simulations are:

- In a Danish context, the district heating plants already have large heat storage installed, demand shifting does not provide high financial gain then. Only if a significant part of the demand is shifted, which is hard to achieve in a system where the heat comfort for the customer is of big importance. In the Brønderslev Forsyning example, the yearly savings were estimated to be 4520 DKK/year.
- In new or existing district heating plants, which do not have heat storage installed, the potential savings achieved with load shifting are much higher. For a system similar to the Brønderslev Forsyning, without heat storage, the savings were estimated to be 0.775 M DKK/year. This approach should be considered, considering other gains coming from the solutions.
- Demand shifting can be useful in reducing the influence of transmission capacity constraints. However, not in situations where the demand exceeds the transmission capacity for a long period of time.
- There is a high potential gain from temperature optimization. Allowing for heat loss reduction and efficiency increase of the production units. The savings on the production site, with a temperature decrease of 5°C, were estimated to be 0.548 M DKK. Temperature optimization can be enhanced by combining information about the buildings and the network.

8. Challenges of CSO from a business perspective

8.1 Recruitment of buildings

A specific challenge in a cross-system optimization implemented as end-to-end, is the engagement of end-users in the buildings. In a CSO context, the desire for cross system optimization is typically coming from the district heating operator, rather than a desire from the building owners or the residents. Therefore, an appropriate incentive and engagement mechanism needs to be adopted to facilitate the uptake of the building-level solution.

Getting access to control in the buildings can be complex and is often time-consuming, where a commitment from the building owners, choice of solution, and access to the place and equipping the first building of a new organisation often be the most demanding part and can fall short of economic viability. The process can be made easier and faster by a good screening of existing setups in buildings in terms of both hardware and building automation systems which often requires commitment and involvement from the building owner side, depending on the size of their building stock and its total energy demand.

Therefore, actors like Neogrid and Leanheat typically target organisations with a large number of buildings (or at least a substantial total energy demand) such as large housing associations or municipalities. In such cases, the selected focus on buildings is typically defined by the customer rather than the network operators and the typical service is building-centric (cost and energy demand reduction).

However, in a CSO context, the geographical placement of the buildings has an important when looking at the alleviation of network-related constraints. In this case, support from the district heating is often a much-needed step To allow effective local integration in the buildings.

The recent years, district heating operators increasingly offer to own and run substations for building owners. This may simplify the engagement of buildings, the communication and increase control possibilities if established.

In large rental residential buildings, a specific problem of customer-driven installation is also that the decision to acquire a controller is made by the organisation operating and owning the building. Provision of such a service will cost a running fee to that organisation, thereby increasing its operational costs, while the benefits will go to the tenants who will get lower heating bills (at least in Denmark where the policy is to provide "cold rent[16]", as opposed to Finland where the "warm rent" approach means that the heating bill is an integrated part of the rent). Therefore, business and incentive models need to take this into consideration To achieve successful market penetration. Building-level optimization can create win-win situations for both buildings and district heating operators if the gains are shared in a fairly and transparently.

[16] In Denmark, you rent your apartment without heating, called here "cold rent". You have to make arrangements for the "warming" yourself and pay separately. In Finland, the flat is rented "warm", which means heated with payment as a part of your renting. This renting model has a direct impact on motivation for energy savings.