Short-term Optimization of the Operation of the CHP District Heating Plant with Heat Accumulator

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Abstract: In this work, the operating cost of the CHP production is reduced by creating optimization model to schedule the operation of the heat storage. The objective function of the model targets to minimize heat production costs and maximize profits of electricity production. To implement the optimization model in practice and automate the operation, the heat storage operation in every normal production situation of the CHP production with its real-life process constraints is modelled. To model the time-variant and non-linear system detailed enough, a MILP (Mixed Integer Linear Programming) model was selected and used to create a piecewise linear model of the system. A sliding time window method was used in the optimization to enable the most optimal heat storage operation in practice. The output of the optimization model is the operation plan of a heat storage for the next day, which provides the smallest operating cost for CHP production. The model can be also applied for heat storage investment planning.

Keywords: CHP generation, Heat storage, District heating systems, Optimal operation and control of power systems, Control of renewable energy resources

1. INTRODUCTION

In Finland, a big share of urban living areas are connected to district heating (DH) systems, where heat power is produced by centralized power plants and delivered to customers by hot water via DH networks. Heat is generated either by heat only boilers or by combined heat and power (CHP) generating units, depending on the power demand of the DH network. Bigger investment for the CHP process has been reasonable in case of big enough heat loads. The total thermal efficiency of app. 90% of CHP generation makes it attractive compared e.g. to 45% of condensing power generation of electricity. [Wiltshire 2016] Nowadays about 30% of the generated electricity in Finland is coming from CHP plants.

However, the evolution of power systems towards increased share of wind and solar-based renewable generation has challenged the utilization of CHP production in district heating applications. Combustion based power generation, both fossil fuel and also biomass fired production is tried to get rid of, and replaced by e.g. heat pump based systems. Some years ago, also the price of electricity went down making the economy of the CHP plants very difficult. The price of electricity was occasionally lower than the price of fuel resulting that many CHP plants minimized their operation costs by bypassing steam turbines and operating on heat only mode. New investments to new CHP plants have been very rare. [Kelly & Pollitt 2010] [Wang et al. 2015]

Due to increasing share of variable renewable generation, volatility of electricity price has increased and the flexibility of the electric power generation has become a very valuable product. The CHP generation is conventionally operated according to the momentary heat load, and electricity production follows the heat load. Thus, the generating capacity of CHP plants is not utilized actively in the control of the electric power systems. [Kaivosoja et al. 2017], [Nuytten et al. 2013], [Laakkonen et al. 2017]

The economy of the CHP generation could be improved remarkably by participating actively to intra-day energy and control power markets by utilizing the control capacity of CHP boilers. The power output of the CHP plants can be temporary decoupled from the heat load by heat storages (heat accumulators) located between CHP units and DH networks. Optimal operation of heat storages to minimize the operation costs of DH systems has been studied widely in numerous investigations. [Christidis et al. 2012], [Streckiene et al. 2009] [Noussan et al. 2014][Zheng et al. 2018] However, most of these studies have been only theoretical without connection to real processes and especially neglecting the constraints derived from the physical characteristics of real systems. Also the role of the uncertainty of load prediction is often neglected. However, operation planning is based on predicted loads for next few days, and in real time operation of the plant, prediction errors may lead to a situation, such as violation of min/max loads of the generation system. In those cases, expensive corrections

such as operation of auxiliary boiler or condenser, are needed to keep the system running.

This paper presents results of a research project aimed to continuously optimize the operation of an existing CHP plant with the heat accumulator. The two main research questions are 1); How much the current operation strategy can be improved by the optimal planning of the operation of the heat accumulator, and 2); What are the effects of a load prediction error and constraints of the real physical system to the optimized operation plan. Chapter 2 introduces the physical structure of the case plant, and chapter 3 presents the formulation of the mixed integer linear programming (MILP) optimization problem. Optimization results are analysed in chapter four and the results are concluded in chapter five.

2. CHP DISTRICT HEATING SYSTEM

2.1. Structure of the Case Plant

The case system consists of a biomass fired CHP plant with 17.8 MW_e electric and 48 MW_{th} heat power outputs, a 4000 m^3 heat accumulator with minimum charging /discharging (ch/dch) power of 2.5 MW_{th} and maximum ch/dch power of 20 MW_{th}. The system is equipped with an auxiliary oil fired heat only boiler (36 MW_{th}) to serve peak loads, and an auxiliary condenser (6 MW_{th}) to drop the minimum DH load still possible to serve by the CHP plant. The structure of the system is depicted in fig. 1.
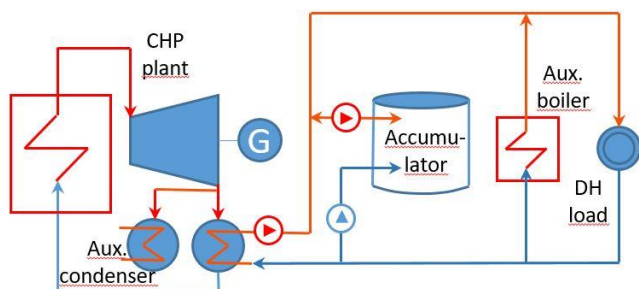

Fig. 1. The structure of the case district heating system.

2.2. Operation of the Case Plant

Most of the time the DH system is supplied by the CHP plant only. The auxiliary heat only boiler is run during peak load hours, when the CHP plant capacity is not sufficient, and when the CHP boiler is down e.g. because of maintenance breaks. The auxiliary condenser is run occasionally during low load periods, when the DH load is below the minimum load level of the CHP plant. The auxiliary condenser can be used also to increase the electricity production during periods with very high electricity price, if the CHP plant is not already operated at the maximum capacity. However, this is very expensive because of the remarkably decreased thermal efficiency of the operation.

In the case system, the current short-term operation strategy of the heat accumulator is based on the hourly changing electricity price. Rule based operation planning tool schedules CHP generation during the hours with the highest electricity price. The power difference between momentary heat load and CHP generation is balanced by the accumulator. The operation of the rule based planning system is disabled when the CHP plant is running at very low or very high loads. The operation planning horizon is 24 hours, which is too short to utilize fully the accumulator capacity. Momentary energy content of the accumulator is not included in the operation planning model, and thus if the min. or max. energy capacity limit of the accumulator is reached, the operation is just stopped. In addition, the accumulator is not automatically used to minimize the use of auxiliary boiler and condenser. These kinds of activities are carried out manually by the operators. The existing system has also some physical dimensioning and structure related limitations such as maximum discharging power of the accumulator must be limited while operating at high load level because of the maximum pressure limits in the DH network. Also minimum charging/discharging powers of the accumulator are limited due to cavitation problems in pumps, and pumps have to be started by slowly ramping resulting to delays in the operation.

3. FORMULATION OF THE OPTIMIZATION PROBLEM

The optimized system is a non-linear and non-convex system due to the operation point dependent operation costs of the CHP-plant, and temporary operation of the heat accumulator, the auxiliary boiler, and the condenser. For the optimization purposes the system is modelled as a piecewise linear and mixed integer system allowing the temporary operation of the auxiliary processes and the accumulator. The structure of the mixed integer linear programming model (MILP) for the system is

$$
\begin{aligned}
&\min \left(cx + dy \right) \\
&s.t. \quad Ax + By \leq b, \\
&x_i \geq 0, \forall i \in I, \\
&y_j \in \{0,1\}, \forall j \in J
\end{aligned}
\tag{1}
$$

where x_i are continuous decision variables and y_j binary decision variables. The decision variables of the model are charge and discharge powers of the heat accumulator, power of the auxiliary condenser, and power of the auxiliary oil fired heat only boiler. Auxiliary variables are used to describe the nonlinearities and discontinuities of the system, such as operation point of the CHP plant, and starting and stopping costs of the accumulator. The binary auxiliary variables applied in the model are: accumulator charging *on*, charging started/stopped at time *t*, accumulator discharging *on*, discharging started/stopped at time *t*, auxiliary boiler *on*, auxiliary boiler has been started/stopped at time *t*.

The objective of the optimization is to minimize the operation costs of the CHP system by minimizing the use of the auxiliary boiler and the condenser, and schedule the CHP generation to time periods with the highest electricity price. Operation costs consist of variable costs of the production and returns of selling electricity. Fixed costs are excluded,

because they are not connected to the operation strategy of the accumulator. The objective function is

$$\min J = \sum_{t=1}^{T} \left(C_{chp}^{t} + Q_{HOB}^{t} c_{HOB} + Q_{aux}^{t} c_{aux} + C_{start/stop}^{t} - P_{chp,net}^{t} c_{p}^{t} \right)$$
(2)

where T is the optimization horizon, C_{chp}^{t} is the operation cost of the CHP plant calculated from the piece-wise linearized characteristic of the plant, $Q_{HOB}^{t} c_{HOB}$ is the operation cost of the auxiliary heat only boiler, $Q_{aux}^{t} c_{aux}$ is the operation cost of the auxiliary condenser, $C_{start/stop}^{t}$ is the starting/stopping cost of the accumulator, and $P_{chp,net}^{t} c_{p}^{t}$ is the value of the generated electric power.

3.1. Constraints

Constraint equation defining the operation range of the system is

$$Q_{boiler}^{\min} \leq Q_{dh}^{t} + q_{s+}^{t} - q_{s-}^{t} + q_{aux}^{t} - q_{HOB}^{t} \leq Q_{boiler}^{\max}$$
(3)

consisting of the DH system heat load Q_{dh}^{t}, accumulator charging and discharging powers q_{s+}^{t}, q_{s-}^{t}, power of the auxiliary condenser q_{aux}^{t}, and power of the auxiliary heat only boiler q_{HOB}^{t}.

The heat only boiler has minimum and maximum loads (Eq. 4), and the minimum operation time of the heat only boiler is constrained to prevent frequent starting and stopping of the boiler (Eq. 5).

$$Q_{HOB}^{\min} \leq q_{HOB}^{t} \leq Q_{boiler}^{\max}$$
(4)

$$yd_{HOB}^{t} \leq 1 - yu_{HOB}^{t-z}, z = 1, \ldots, \Delta t_{HOB}^{\min}$$
(5)

Operation of the auxiliary condenser is constrained only by its maximum available power

$$q_{aux}^{t} \leq Q_{aux}^{\max} .$$
(6)

Operation of the heat accumulator is constrained by the minimum and maximum energy contents and maximum charging/discharging powers. The available energy content of the accumulator is related with the inlet and outlet water temperatures of the DH network. In addition, the heat accumulator cannot be charged, if the inlet water temperature of the DH network exceeds the maximum temperature limit of the accumulator. This is the case during the coldest winter days, when the inlet temperature of the DH network is between 110 – 115°C, but the max. temperature of the accumulator operated in atmospheric pressure, is below 100°C. In order to avoid cavitation in the accumulator charging and discharging pumps, also the minimum available charging/discharging power for the accumulator is constrained. The non-linear ramping function applied in the starting of the pumps is replaced in the model by a linear delay function.

3.2. Sliding Time Window Method

When solving the optimization problem to minimize the operation costs of the CHP plant with heat accumulator over the time horizon, the optimal solution utilizes all the stored heat in the accumulator to minimize the operation costs. Thus, the accumulator will be always emptied towards the end of the optimization horizon. However, in case of the continuous operation of the plant, this is not the optimal way. This problem is tackled by using a sliding time window method [Fang et al. 2015], where the optimization horizon is set to a certain length, but the new optimal control schedule is calculated already after the first half of the previously optimized schedule has been put into practice.

The optimal length for the optimization horizon was found by searching the horizon resulting to the lowest operation costs. When the length of the optimization horizon is increased, the load prediction error will also increase, effecting on the optimality of the calculated solution. The length of the optimization horizon T is a case specific parameter for individual systems depending on the load prediction accuracy, capacity and characteristics of the system, and constraints. For our case system, the optimization horizon was chosen to be three days (Fig. 2).
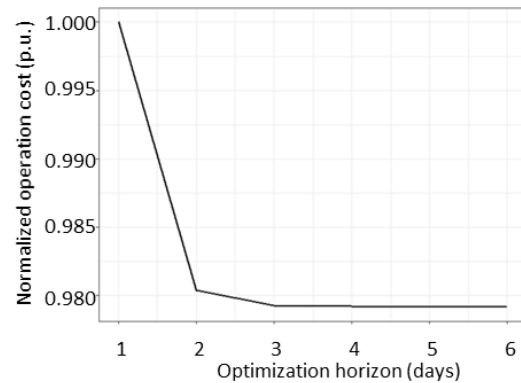

Fig. 2. Selection of the length of the optimization horizon.

The optimization problem was formulated by using R modelling language, and the problem was solved by using the CPLEX solver. [IBM 2018]

4. RESULTS

Performance of the optimization system was evaluated by comparing the simulated optimized operation of the system with the real operation from history data for one-year period from 5/2017 to 4/2018. Simulation was carried out by using the same predicted DH load, which was applied in the realized operation planning. Therefore, because of the equal presumptions, the results are comparable with each other.

As a result, the annual operation costs were reduced by 2,3 % by operating the accumulator according to the optimized planning. The optimized operation would have increased the total amount of energy produced by CHP plant and decrease the use of auxiliary boiler and condenser. Table 1 shows that the biggest improvement to the operation costs is achieved

from rescheduling CHP generation to hours with high electricity price. The next biggest improvements were gained from the reduced use of the auxiliary boiler and condenser.

Table 1. Factors reducing the operation costs of the CHP plant

Factor	%	MWh
Increased electricity production	-0.42	374.5
Rescheduling of the el. production	-1.17	-
Reduced use of auxiliary boiler	-0.52	-1070
Reduced use of aux. condenser	-0,27	-236
Operation with better efficiency	0.08	-
Tot. change of the operation costs	**-2.3**	**-**

On the other hand, the increased use of the CHP plant has resulted also to the increased operation in the range where the thermal efficiency is worse, but the effect of this to the total costs is negligible.

Fig. 3 shows the effects of the optimized operation planning compared with the realized operation costs. The upper diagram shows the weekly DH load in megawatts from May/2017 to April/2018. During weeks 26 – 34, the CHP boiler was switched off because of the maintenance break. The lower diagram shows the changes of the operation costs when compared the realized costs to the optimized operation costs. The colour code of cost change bars indicate if the existing accumulator operation planning tool has been switched "on" (green) or "off" (red). On-status is stated, if the system has been switched "on" more than 70% of the time of the week, and "off" if less.
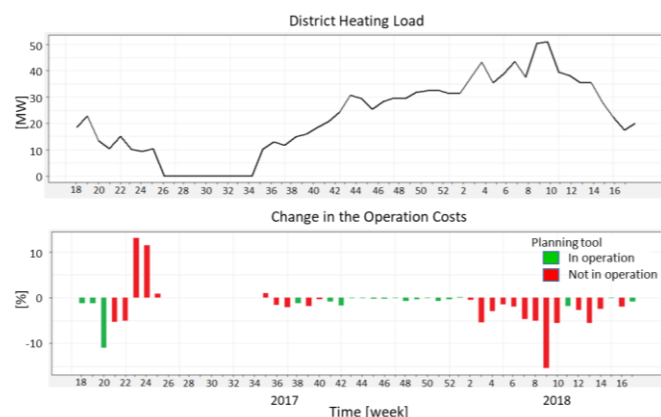

Fig. 3. Effects of the optimization to the actual operation costs week by week.

The results show that the momentary load effects on the gained improvements. The highest gains were achieved at low and high loads. The reduced costs were a result from the reduced operation of the auxiliary boiler during high loads and the reduced use of the auxiliary condenser during low loads. When operated on medium load level, weeks 40/2017 – 2/2018 the cost reduction was minor, because the CHP-plant was able to supply the DH load without the use of auxiliary systems. The gains achieved during this period came mainly from the rescheduling of the generation to the

periods with higher electricity price by the more effective use of the accumulator.

Optimized operation during weeks 23, 24, 25 and 35 differs from other weeks because the optimization increased the operation costs compared with the realized situation. During these weeks the heat load has been low, and the accumulator was operated manually (red bars). The intraday variation of the heat load was smoother compared with the previous weeks resulting to big load estimation errors. Because of the erroneous load estimate, the optimized operation discharged the accumulator too much resulting to increased use of the auxiliary condenser to keep the CHP boiler on the operation range. A detailed behaviour of the system during weeks 23 and 24 is shown in fig. 4. Top diagram shows the optimized (blue) and realized (black) charging (+) and discharging (-) of the accumulator, diagram in the middle shows the predicted and realized DH loads, and the lowest diagram shows the predicted and realized spot prices of electricity.
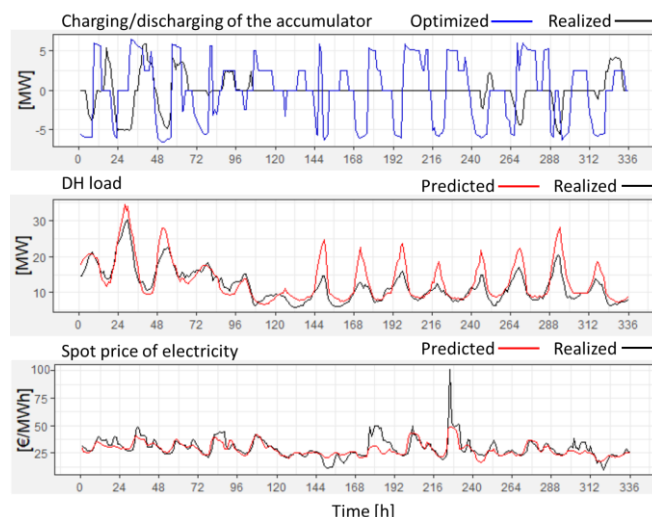

Fig. 4. Optimized and realized operation of the system during weeks 23 and 24.

Due to the load prediction errors, the planned operation of the accumulator would have violated the constraints set for the operation of the CHP plant. Balance errors caused by this were compensated by additional use of the auxiliary condenser resulting to increased operation costs.

Fig. 5 shows the use of the auxiliary condenser as a function of the DH load estimation error in case of a low DH load. Because of the erroneous load estimate, the accumulator was not utilized to store the excessive energy from the CHP plant, but the energy had to be dumped into the condenser. In case of the zero estimation error, the optimized use of the auxiliary condenser would have been like shown in figure 6.

When operating at high loads near the maximum capacity of the CHP boiler, the existing operation planning system is switched off because the CHP capacity is almost totally in
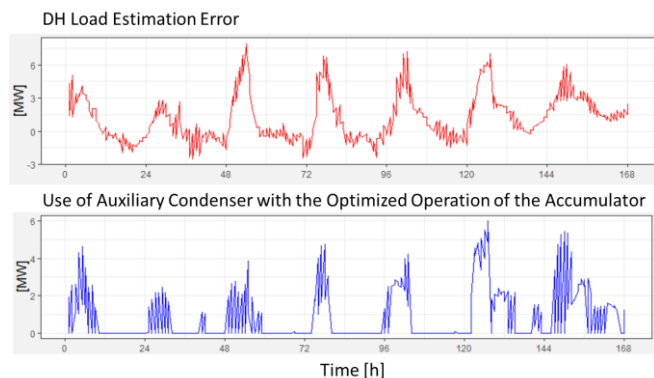
Fig. 5. Connection between the load estimation error and the required use of the auxiliary condenser.
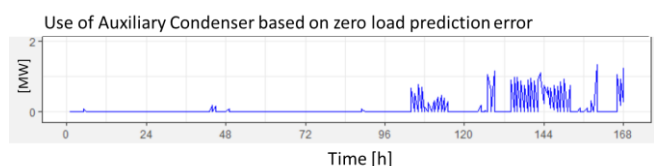

Fig. 6. Use of the auxiliary condenser if the estimated load in optimization would have been error free.

use and cannot be rescheduled. Due to this, the accumulator is operated manually and the minimization of the use of the auxiliary boiler depends on the activity and capability of the operator.

Fig 7 shows detailed information about the operation of the system at high load. The figure shows that the optimized operation utilizes the accumulator much more effectively. The estimated load and spot price of the electricity follows also pretty well the actual values.
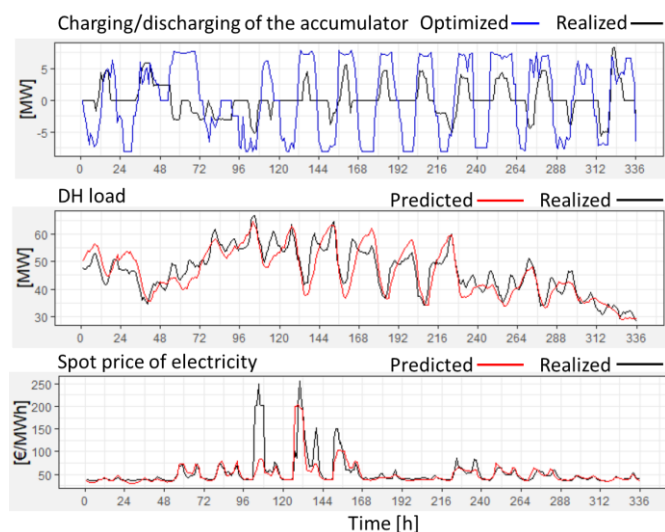

Fig. 7. Optimized and realized operation of the system during weeks 9 and 10 on 2018.

Fig. 8 shows the use of the auxiliary boiler at high load with and without the optimization of the operation of the accumulator. As seen, the use of the auxiliary boiler is reduced as a result of optimization of the heat accumulator.
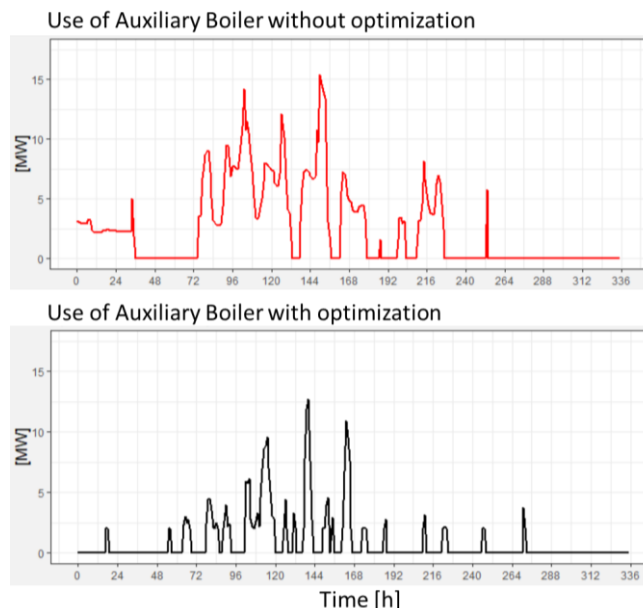

Fig. 8. Use of the auxiliary boiler without and with the optimized operation of the accumulator at high load during weeks 9 and 10 on 2018.

4.1. Load Prediction Error

The effect of the load prediction error to the optimality of the operation planning was evaluated by repeating the simulations with actual realized load and with the load estimate calculated as a mean value between the estimated and realized loads. Table 2 shows the results with halved and zeroed prediction errors to the operation of auxiliary boiler and condenser

Table 2. Effect of load prediction error to the operation of auxiliary systems

	Orig. pred. error	Halved pred. err.	Zero pred. error
Auxiliary boiler [MWh]	600	374	97
Auxiliary condenser [MWh]	727	371	57

4.2. Process constraints

Analysis is based on removing the operational constraints firstly one by one, and secondly by removing them all, and comparing the results with fully constrained case. The examined scenarios are: 1) The accumulator can be operated with maximum discharge power despite of the DH load; 2) Starting and stopping of the charging/discharging of accumulator without delays; 3) The minimum operation point of the accumulator is 0MW (no pumping related constraints); 4) The accumulator can be discharged fully empty to 0 MWh; 5) The maximum energy content of the accumulator is a constant, not related to DH-water temperatures; 6) all the constraints are removed.

The most meaningful constraints could be removed from the existing systems by improved generation planning, control engineering, and minor changes to the process equipment. E.g. maximum operation power can be made independent from the DH-load by system level production planning including also the operation of the DH-network. Minimum operation power can be lowered by installing smaller pumps parallel with the main pumps. Minimum and maximum energy contents of the accumulator depend on the dimensioning of the accumulator and cannot be changed without expensive process modifications (for existing systems).

Table 3. Effect of the process constraints to the operation costs and operation of the accumulator

	Operation costs [%]	Price of gen. elec. [%]	Operation hours of acc. [%]
Max. acc. operation power constant	-0.27	0.60	0.55
Undelayed acc. operation	-0.17	0.07	1.12
Min. acc. oper. power = 0	-0.18	0.57	0.55
Min. energy content of acc. = 0	-0.06	0.02	0.54
Max. energy content of acc. constant	-0.06	0.01	1.19
Total effect	-0.74	0.97	5.38

5. CONCLUSIONS

The results show that with short term planning and optimization of the heat accumulator, it is possible to improve the profitability of the CHP-generation several percents compared with the current operation. The sliding time window method worked well and was useful especial in the peak shaving and smoothing of thermal loads. The goal of the objective function was to minimize the operation costs by scheduling the CHP generation to the hours with highest electricity price and by minimizing the use of expensive auxiliary condenser and heat only boiler. The biggest problem in automatized optimized operation planning was the uncertainty of predicted loads resulting to unnecessary use of auxiliary condenser and boiler. Impact of the operational constrains of the accumulator were small compared with the impact of prediction errors.

In future, when changing from hourly based energy markets to 15 min based market, the impact of operational constraints may increase, such as the starting delay and ramping of accumulator pumps. Furthermore, to be able to utilize the whole potential of the accumulator, instead of optimizing the operation of the CHP plant, the operation of the whole DH system should be optimized. This will increase the system complexity, modelling effort, and the computational effort needed to solve the optimization problem.

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