

Optimization of District Heating Systems: European Energy Exchange Price-Driven Control Strategy for Optimal Operation of Heating Plants

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Abstract

District heating (DH) systems are often seen as a good practical approach to meet the local heat demand of districts. Yet, under today's regulations to renovate buildings on high efficiency standards, the local heat demand is decreasing. Therefore, the operation of DH systems is also affected by the changing heat demand profile, which might lead to less profit for the operators of DH systems. Thus, the operators strive for an optimal operation at which the heat demand is met and the profits are maximized. In this work, a control strategy for optimal operation of a combined heat and power (CHP) based DH is presented. The proposed control strategy couples the operation of CHPs to the European energy exchange (EEX) price by implementing different operation constraints. This configuration is accompanied with another, which is the installation of additional storage volume. Thereby it is held to provide the optimal operation for the plant technically and economically.

Keywords: Modelica/Dymola, District Heating, Heating Plant, Power-Based Model, Optimal Operation, Control Strategy, Storage.

1 Introduction

District heating (DH) systems represent a key energy solution that have been deployed for years in a growing number of cities worldwide (Werner, 2017) (Rezaie, B. and Rosen, M. A., 2012). Thereby, DH systems are envisioned as an effective approach to provide affordable, local and low-carbon energy to the consumers through diversity of supply, energy balancing and storage (Guelpa et al., 2018). Therefore, DH systems are envisioned as one of the practical approaches for the global transition to sustainable energy utilization in many urban centers (Fiacro Castro Flores, 2018).

Moreover, combined heat and power (CHP) based DH systems are seen as a flexible heat-supply option as it provides heat to meet the local heat demand in urbans and, therefore, these CHPs are frequently heat driven (Elci et al., 2015). CHP produces also electricity as a byproduct and feeds it into the national power grid

helping in balance it due to the fluctuating renewables, especially during periods where renewables hardly provide useful energy (Buffat, R. and Raubal, M., 2019). Consequently, CHP's electricity is fed into the grid at a variable or fixed tariff depending on the European energy exchange (EEX) market. Thus, this fed electricity might lead to gain profits out of the electricity produced.

In the coming years, it is believed that buildings' heat demand will gradually decrease due to the refurbishment regulations. The goal in the refurbishment process is to have energy demand as low as possible. This demand profile and the national electricity demand fluctuate seasonally and hourly with asynchronous patterns, thus it is important to guarantee an optimal-operation of the heating plants coupled to the DH networks. Thus, the operators of DH systems strive for an optimal operation at which the heat demand is met and the profits are maximized (Dahash et al., 2017). Consequently, it is of importance to introduce an optimal-operation for the heating plants coupled to DH networks.

Furthermore, this operation strategy should be subjected not only to the buildings' heat demand, but also to electricity selling price in the market, fuel costs and electricity demand in the national power grid. In this context, it is pointed out that such an optimal operation is a future challenge in DH domain due to the complexity, the high number of parameters and its combinatorics and the optimal planning for heat-generation between the different heat sources in the heating plant (Zhou et al., 2014). Following this challenge, it is highly advised to rely on decision support/making tools, which are dependent on model predictive control (MPC) to achieve the optimal operation (Giraud et al., 2017).

In this study, we present a control strategy for optimal operation of CHPs in heating plants coupled to DH networks. In this control strategy, the electricity market price is introduced to take advantage of the periods during which the electricity price is relatively high to maximize revenue. To test this strategy, a validated power-based model of a DH system is used. This model shows the amount of energy flows between the different parts of the DH system (supply side,

transmission network and demand side). The reasons behind this modeling approach are the less simulation time and the better insight in the heating plant's operation (Dahash, 2016). For the modeling, Modelica/Dymola was used as a simulation tool since Modelica supports the description of mathematical equations following the physical modeling paradigm.

2 Methodology

2.1 Case Study

As a case study, a district in the city of Freiburg in the south of Germany was used. This district is called Weingarten and it was built in the 1960s. Under current regulations regarding comfort, energy efficiency and modern building technology, the buildings in the western part have to be renovated into more energy-efficient buildings. This refurbishment requires major structural, technical and economic interventions in order to modernize the district's buildings, renew Weingarten's energy supply system and operate it optimally.

The district's heat demand is provided by a central heating plant that supplies heat to two districts (i.e. Rieselfeld, Weingarten) via a DH network as shown in Figure 1.

In the heating plant, 6 gas-fired CHP units, each with $1200 \text{ kW}_{\text{el}} / 1490 \text{ kW}_{\text{th}}$, are installed and the operation of them is mainly heat-driven. Consequently, two CHP units are operating almost continuously year-round to meet the base-load. Thus, over 75 % of the annual amount of heat produced comes from CHP units, while the remainder is generated by peak boilers ($3 \cdot 9300 \text{ kW}$). Also, in order to achieve smooth operation of the CHP units, there are two thermal energy storage (TES) systems with a total volume of 360 m^3 . They help in meeting the demand over short periods.

2.2 DH System Model Description

A thermo-hydraulic model of a DH system with fully described details requires high computational efforts (simulation time), particularly when modelling large DH systems with many heat supply technologies, consumers, long-distance networks and complex operation scheme. Accordingly, it is important to reduce the complexity of the models to a degree in which all physical properties remain accurate. Thus, it is vital to underline the crucial goal of modelling process in order to reduce the computational efforts and time (Dahash et al., 2019).

In this study, the main goal is to simulate correctly the operation of the central heating plant and to test the proposed control strategy and its applicability with another optimization configuration (installing additional TES volume). As a result, many general assumptions are

set in the system layout in order to simplify the model. These assumptions are as follows:

1. The demand side (consumers) is modelled as a single heat sink. This sink is directly connected to the network. This means there is only one single loop in which the heat sink is directly coupled to the network without the need of heating substations.
2. The three peak boilers in the heating plant are represented in a single equivalent boiler with a total thermal power of 27,900 kW.
3. Since the two TES units are connected in series in the heating plant, it is possible to represent them as one single unit. Therefore, a single TES unit with a total volume of 360 m^3 is implemented in the model.

The heating plant model used in this study is extensively described in an earlier study (Dahash et al., 2017). Also, the validation of this model was carried out in the aforementioned literature. Therefore, only the control strategies are comprehensively discussed in the following sections in order to comprehend the changes in the control strategy and to compare the results. Moreover, the reference and the proposed control schemes for the CHP are presented, whereas no changes are seen necessary for the boiler and storage controllers.

2.3 Reference Control Strategy

2.3.1 CHP Controller

Herein, the bottom segment temperature for storage is set to 70°C and the upper one is set to 100°C . For each CHP unit, an individual CHP controller is installed in the model. In this controller, the heat demand and the storage temperatures (upper and bottom) are simultaneously checked. From Figure 2, 3 cases can be determined to run the CHP unit, which are:

1. **Power case (a):** if the heat demand is higher than the nominal CHP's heat output and the temperature of the bottom segment is higher than 70°C , then the CHP unit runs.
2. **Power case (b):** if the heat demand is higher than nominal CHP's heat output and the temperature of the bottom segment is lower than 70°C , then the CHP unit runs.
3. **Power case (c):** the CHP unit runs, when the following conditions are all true:
 - i. The heat demand is lower than nominal CHP's heat output, and
 - ii. The heat demand is higher than 95 % of the CHP's heat output (equals 1.425 MW), and

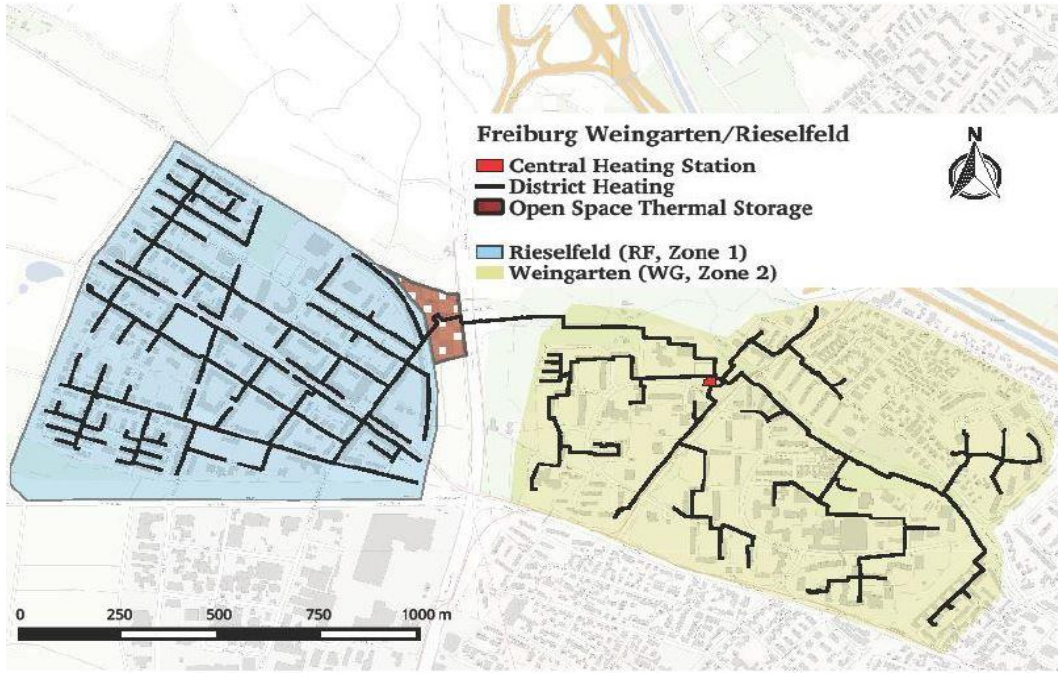


Figure 1: Geographical top view of the Weingarten and Rieselfeld district with the central heating station and DH network (Bachmaier et al., 2015)

- iii. The upper storage temperature is lower than 95°C.

Regarding power case (a), as the storage temperature is equal to or higher than 70°C, this means the storage can be discharged. On the contrary, if the storage temperature is less than the set bottom temperature (70°C), this means the energy stored in the storage system cannot be used and, therefore, power case (b) is activated to supply the heat directly to the consumers. While power case (c) is activated in order to cover the heat demand that is higher than 1.425 MW and the remaining of the heat output charges the storage.

Moreover, if the heat demand (or the remaining heat demand for CHP 2-6) is less than 1.425 MW or the upper storage temperature is higher than 95°C, then the corresponding CHP unit turns off.

2.3.2 Storage Controller

This controller plays a role in the energy balance of the entire heating plant, since it gives a signal to discharge or charge the storage system. The controller flowchart is shown in Figure 3. Therein, it is illustrated that there are two inputs and a single output. One input is the storage bottom temperature. Based on the temperature, a decision is made as whether the storage system can be discharged.

If the temperature of storage's bottom, however, is higher than 70°C, this sends a true signal to the switch component to discharge the storage system to cover the

remaining demand. Otherwise, the output is set to zero when the temperature is less than 70°C. Thus:

$$\dot{Q}_{\text{storage}} = \dot{Q}_{\text{demand}} - \sum_{i=1}^6 \dot{Q}_{\text{CHP},i} \quad (1)$$

Occasionally, the storage system cannot be discharged because the last segment temperature is less than that allowed for discharging and, therefore, the remaining heat demand proceeds to the next controller, which is the boiler controller that runs the boiler in order to meet the required amount of heat.

2.3.3 Boiler Controller

The boiler controller is a simple unit, which computes how much heat demand remains after the total output of the CHP units and the discharged capacity of the storage system. Next, it gives an output signal to run the boiler in a partial mode to meet the remaining heat demand, thus:

$$0 \leq \dot{Q}_{\text{boiler}} \leq 27.9 \text{ MW} \quad (2)$$

Here, the remaining demand is computed as below:

$$\dot{Q}_{\text{boiler}} = \dot{Q}_{\text{demand}} - \sum_{i=1}^6 \dot{Q}_{\text{CHP},i} - \dot{Q}_{\text{storage}} \quad (3)$$

The term \dot{Q}_{storage} refers to the usable heat in the storage system. Therefore, the usable temperature lies between 70°C and 100°C.

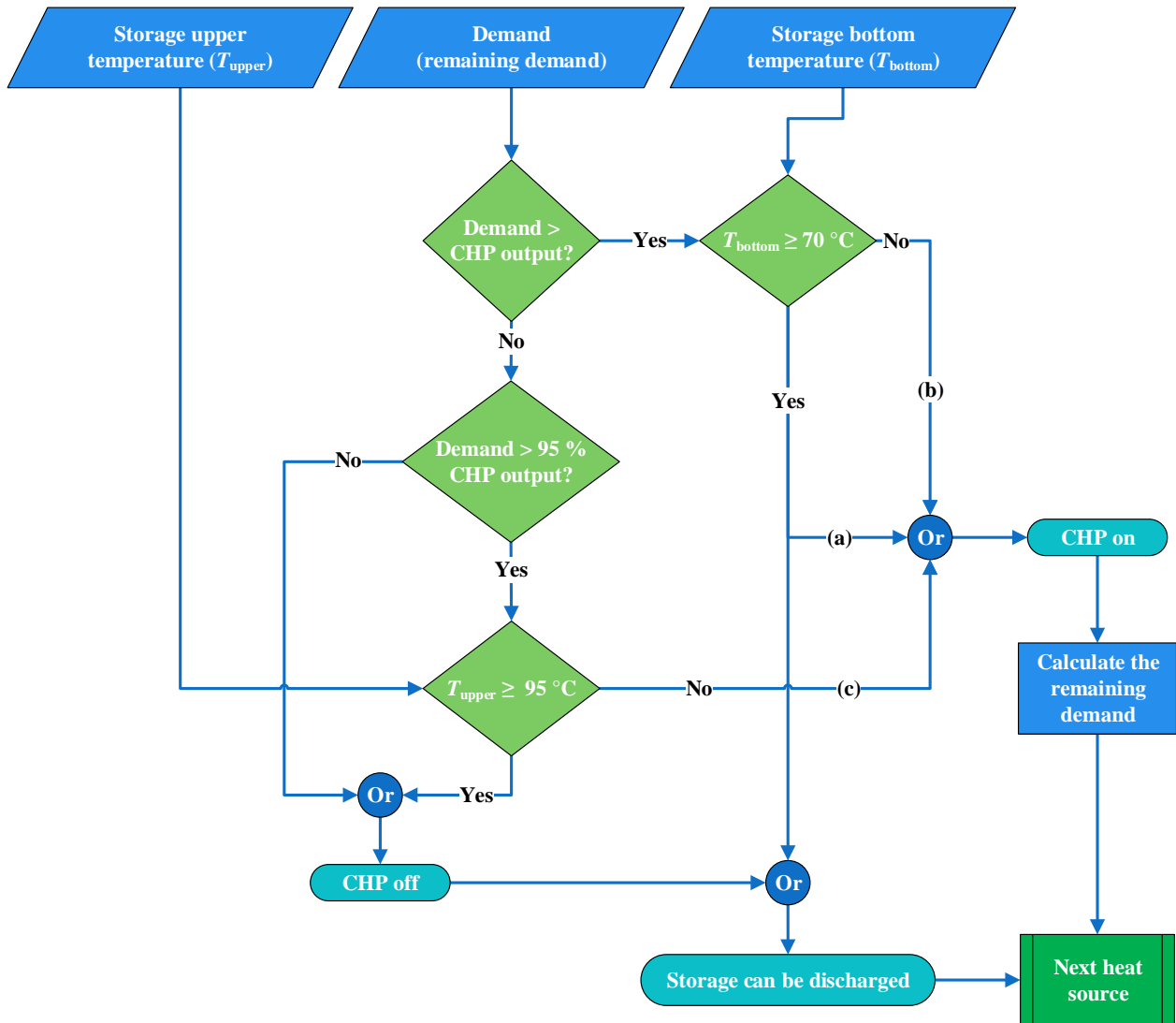


Figure 2: CHP controller flowchart (reference case).

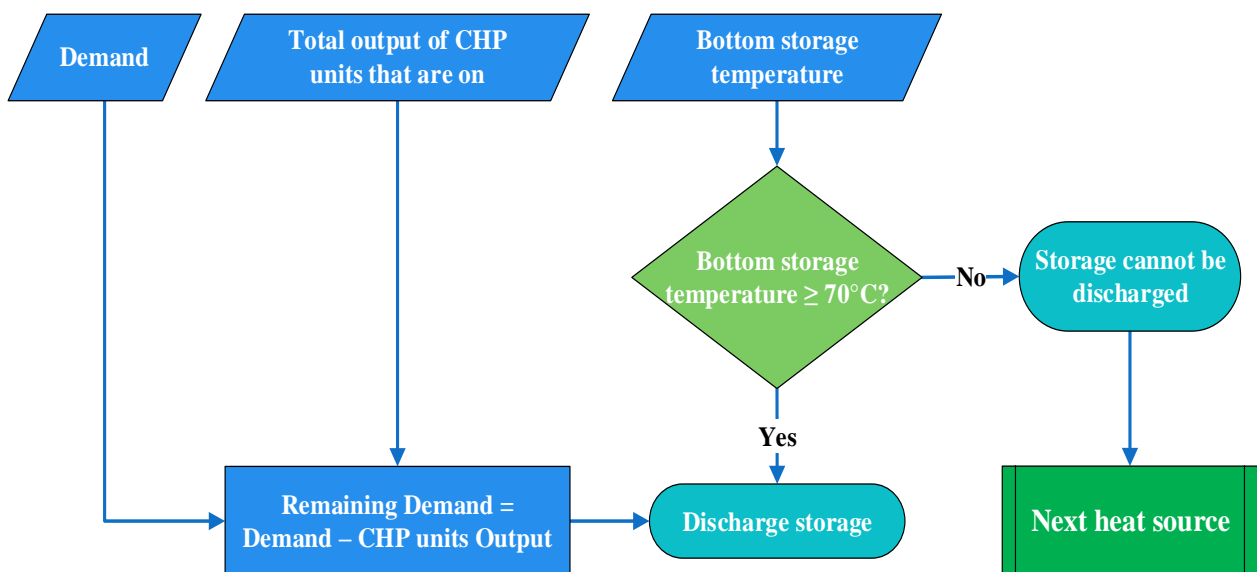


Figure 3: Storage controller flowchart.

2.4 Proposed Control Strategy

In this control strategy, the major changes take place in the CHP controller, as it is the primary regulator of the heating plant. Firstly, a price threshold is determined and implemented in the CHP controller. Then a constraint is set in the controller, if EEX price is higher than this threshold, then it is worthwhile to run the CHP units to maximize the revenue regardless of the heat demand. Nevertheless, the following question arises: **What if a situation occurs where the storage is fully charged, the EEX price is high enough to run the CHP units and the heat demand is relatively low?**

Having considered this scenario, the control strategy is constructed such that if the heat demand is high and EEX price is lower than the threshold, the CHP units run to meet the demand and the rest is stored. Accordingly, the storage is set to a predetermined temperature. In addition, when EEX price is more than the threshold, the CHP units run to feed the electricity produced into the grid and the storage is charged until 100°C (fully charged) regardless of the heat demand. Furthermore, to determine the optimum storage temperature to fulfill the energy balance constraint, an iterative algorithm is built as shown in the Figure 4.

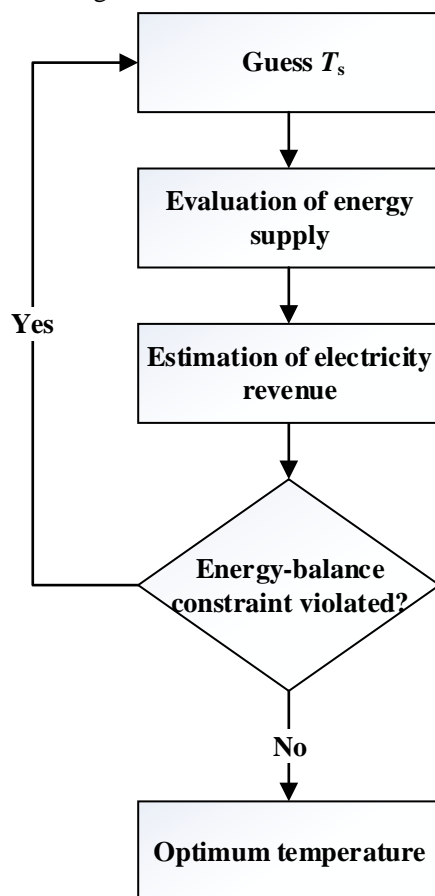


Figure 4: An iterative approach to determine the optimum storage temperature.

Figure 4 illustrates that firstly, a guess for the storage temperature is made, and it is assumed 80°C, and then the simulation runs until the energy supplied by the heating plant is seen. Next, the energy-balance constraint is inspected, if it is true and there is a balance, then optimum storage temperature is found. If not, then another guess is made and the simulation runs again until the energy balance constraint is fulfilled. Following this iterative approach, the optimum storage temperature is determined to be 86°C and the price threshold is set to a specific value (e.g. 36 €/MWh), at which the energy-balance constraint is fulfilled. Thus, the storage capacity is used up to 86°C when there is a heat demand regardless of the EEX price. Whereas the rest of storage capacity (86°C up to 100°C) is kept for periods at which EEX, price higher than the threshold.

Essentially, the CHP units are forced to run when the electricity price is high even though there is no heat demand. Therefore, the heat can be stored in the TES and the electricity is fed into the grid and sold for high prices. Figure 5 illustrates the flowchart for this proposed controller, and it is seen that there are 4 power cases to run the CHP unit.

The power cases are:

1. **Power case (a):** if the heat demand is higher than the nominal CHP's heat output and the EEX price is higher than 36 €/MWh, then the CHP unit runs.
2. **Power case (b):** if the heat demand is higher than nominal CHP's heat output and the temperature of the bottom segment is lower than 70°C, then the CHP unit runs.
3. **Power case (c):** if the heat demand is higher than the nominal CHP's heat output and the temperature of the bottom segment is higher than 70°C, then the CHP unit runs.
4. **Power case (d):** if the heat demand is lower than the nominal CHP's heat output and the EEX price is higher than 36 €/MWh, then the CHP unit runs.

It is worth to mention that if the power case (d) is activated, this means the heat demand is lower than CHP's heat output and, therefore, the demand is met firstly and the rest goes to the storage to be stored. The storage here is allowed to store heat up to 100°C, this matches (f) in Figure 5. While if the EEX price is lower than 36 €/MWh, then the storage is allowed to store the heat at a maximum temperature of 86°C regardless the heat demand as seen in the flowchart above, this matches line (e) in the flowchart. Also, in case the heat demand is higher than CHP's heat output, then the CHP unit runs regardless the EEX price and this constraint is covered by power cases (b) and (c). Moreover, in the below flowchart, the cases to discharge the storage are not shown.

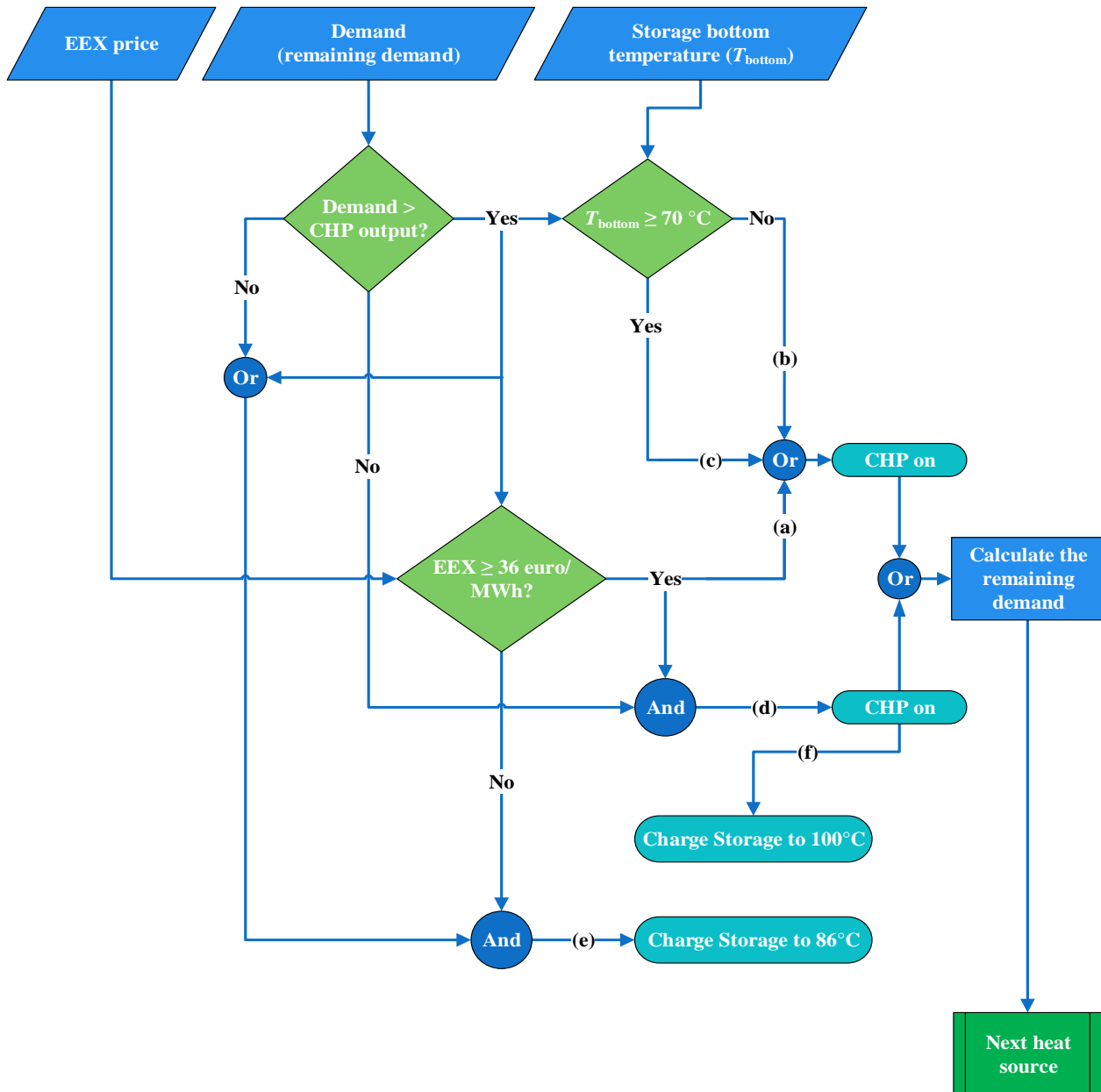


Figure 5: CHP controller flowchart (proposed case).

2.5 Techno-Economic Governing Equations

The energy consumed (gas) to cover the production of heat and electricity from a CHP is computed as:

$$Q_{\text{fuel}} = \frac{Q_{\text{th}} + E_{\text{el}}}{\eta_{\text{tot}}} = Q_{\text{gas}} \quad (4)$$

Same equation (4) is also applied to calculate the thermal energy produced by and energy supplied to the boilers, as they only produce heat. Additionally, the total cost of fuel energy supplied (i.e. gas) to the CHP or the boiler is given by the following equation:

$$C_{\text{gas}} = c_{\text{gas}} \cdot Q_{\text{gas}} \quad (5)$$

c_{gas} is the specific cost of the gas as stated in the contract between the gas supplier and the heating plant operator. It is taken as 30 €/MWh, whereas C_{gas} is the cost of gas in euros.

As the heating plant operator, Badenova, sells the heat produced with a mean price of 5.5 cent/kWh calculated out of Badenova's pricing sheet, the revenue gained from the heat produced is also computed as below:

$$R_{\text{heat}} = c_{\text{heat}} \cdot Q_{\text{demand}} \quad (6)$$

On the other hand, Badenova does not sell the electricity generated at a fixed price due to a varying EEX price in electricity market. Thus, it is possible to implement the variable electricity price in the future and, therefore, the electricity revenue is calculated as below:

$$R_{\text{electricity}} = \int_0^t P_{\text{el}} \cdot c_{\text{el}}(t) \cdot dt \quad (7)$$

c_{el} is the current electricity price in EEX in [€/MWh].

All these equations are implemented in Dymola as computational units for both operations (reference and proposed) to compute the different parameters (thermal energy production, electricity generation, gas consumption, revenues and costs). After calculating these values, the annual net profit of each operation is calculated as below:

$$NP = R_{\text{heat}} + R_{\text{electricity}} - C_{\text{total}} \quad (8)$$

C_{total} is the total cost of gas supplied to the heating plant for both of CHP units and boilers.

3 Simulation Results and Discussion

The determination of the storage temperature is the most critical aspect in order to avoid violating the energy-balance constraint. Therefore, many simulations were carried out following the iterative procedure that is described in Figure 4. Nevertheless, only the results of successful simulations are considered here and compared with the reference case of the model (the normal CHP controller).

The simulation results reveal a slight increase in the operation of CHPs during the years 2014, 2015, 2016 and 2020 compared to the reference operation. In these scenarios, year 2014 represents the buildings' heating demand before the refurbishment, whereas the years 2015 and 2016 stand for the status during the refurbishment. Year 2020 represents the forecasted heating demand when the buildings are completely renovated into more energy-efficient ones.

Furthermore, the increase in CHPs operation is accompanied by a reduction in the produced heat from boilers as seen in Figure 6.

Yet, Figure 6 depicts that the CHPs' heat output decreases as the price threshold increases from 30 €/MWh up to 45 €/MWh. This is because the period in

which EEX price around 30 €/MWh is more frequent compared to both other periods. Therefore, more heat is produced from the boilers during periods with high price threshold. If the price threshold is set to 45 €/MWh and EEX price is around 30 €/MWh, then the CHPs operation will not be feasible since they run in full-load and, thus, they demand high gas consumption. So, they generate electricity, which will be sold at low EEX price and, then, low profits. Whereas it is more feasible to run the boilers since they can run in partial load and cover the low heat demand fully.

As a result, the total gas consumption also varies, which also has in return an influence on the economic feasibility of the new control strategy. However, since the operator of the heating plant buys gas with a fixed price, then the changes in gas consumption have minor influence on the economic feasibility compared to the influence of EEX price.

To increase the feasibility of this control strategy, additional TES units are installed. Each unit with a volume of 210 m³. The additional volume will allow the CHPs to run smoother, longer and more flexible during periods at which EEX price is high enough. During such periods, the heat demand is met, whilst the remainder of produced heat is stored in TES. When heat is needed later and EEX price is low, then there is no need to run the CHPs or the boilers. It could be enough to discharge TES and if more heat is needed, then the boilers run.

Out of the results, it is decided to select years 2016 and 2020 and show their results in context of CHPs and boilers heat output to demonstrate that increasing the TES volume with such a controller might lead to less operation of boilers and CHPs can run longer and, hence more profits.

Figure 7 and Figure 8 illustrate the amount of heat produced by CHPs and boilers with an increasing TES volume for the selected years (2016 and 2020).

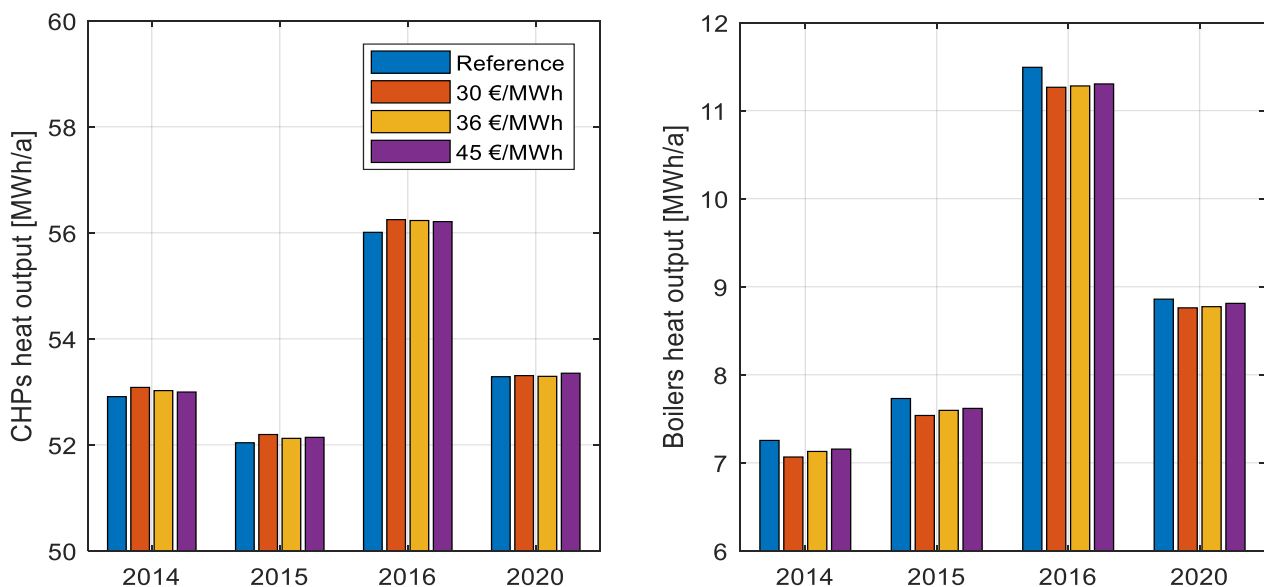


Figure 6: Comparison of CHPs' and Boilers' heat output for three price thresholds compared to the reference case (blue bar) during the years 2014, 2015, 2016 and 2020 (All cases are subjected to $V_{\text{TES}} = 360 \text{ m}^3$).

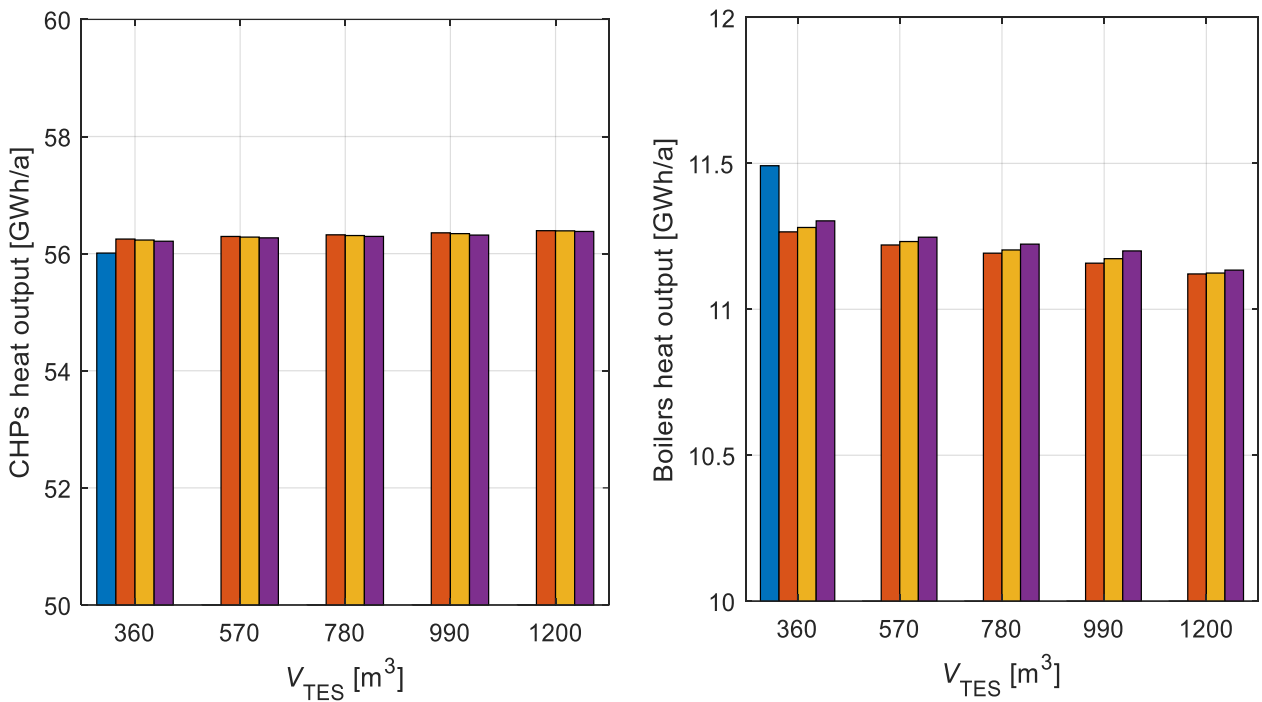


Figure 7: Comparison of CHPs' and Boilers' heat output for three price thresholds compared to the reference case (blue bar) during the year 2016.

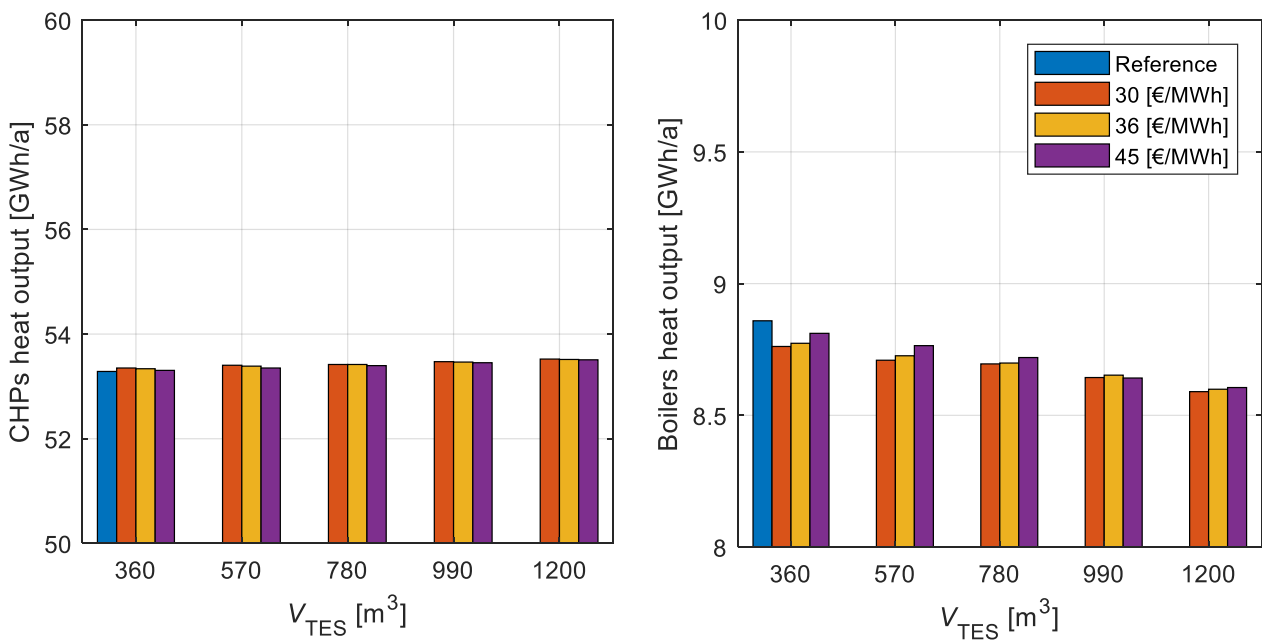


Figure 8: Comparison of CHPs' and Boilers' heat output for three price thresholds compared to the reference case (blue bar) during the year 2020.

The annual net profit is calculated for each scenario following equation (8) and then compared to the reference scenario to display the annual net profit

percentage (ΔNP (%)) in Figure 9. The net profit percentage is computed from the following equation:

$$\Delta NP (\%) = \frac{(NP)_{pro} - (NP)_{ref}}{(NP)_{ref}} \cdot 100 \quad (9)$$

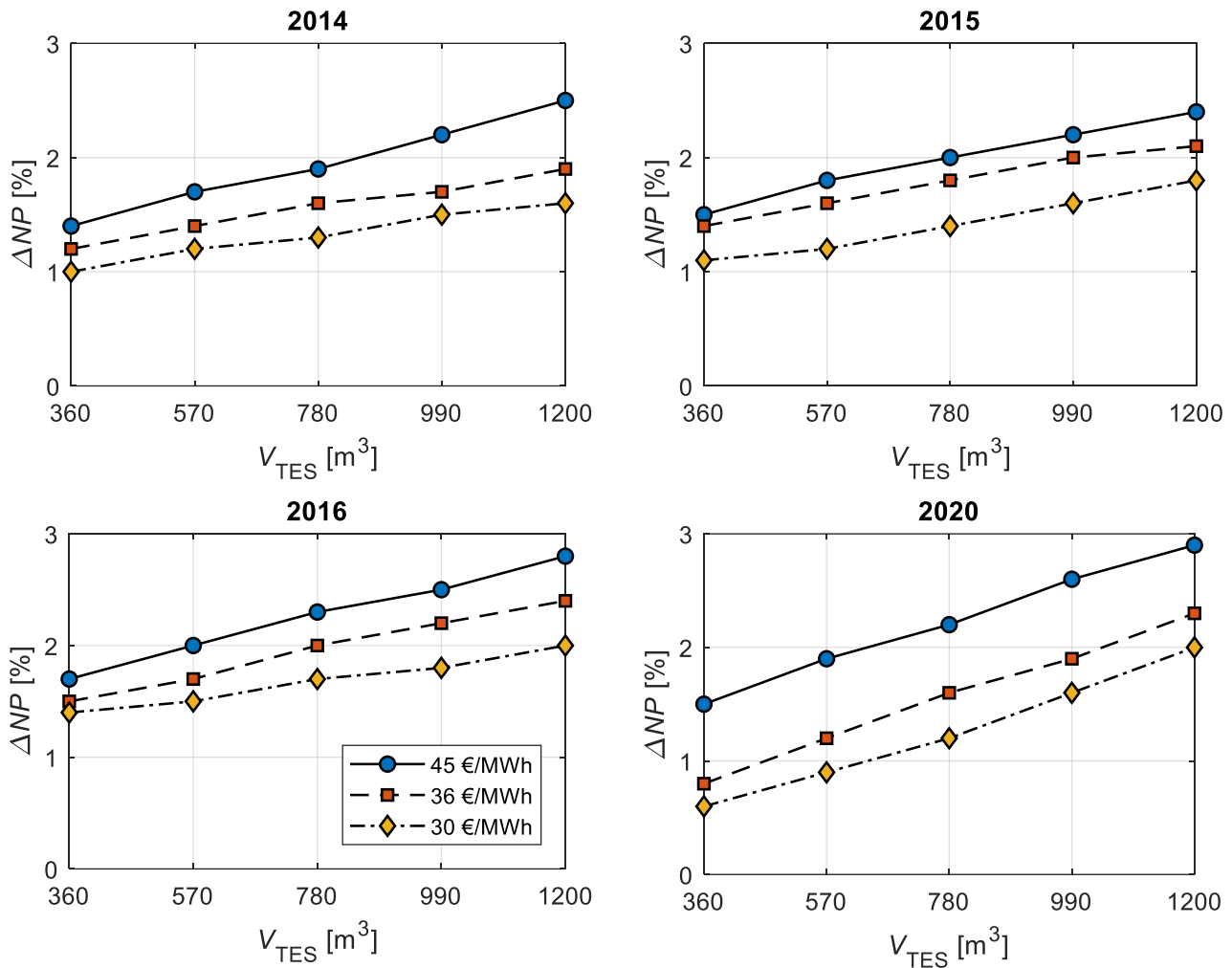


Figure 9: Net profit percentage for the proposed control strategy at different storage volumes compared to the reference case (reference control strategy and $V_{TES} = 360 \text{ m}^3$).

It is worthwhile to mention that the control strategy is seen not highly beneficial in year 2020 for the TES volume of 360 m^3 . This is attributed to the expected negative EEX prices in the corresponding year, which in return is due to higher electricity share from renewables. Therefore, a drop in EEX prices is expected. Thus, the CHPs run for less time during these periods.

The results pinpoint that this control strategy is held to be feasible, especially in the cases with a TES volume beyond 360 m^3 . This volume increase enhances the operation of the heating plant and maximizes the profits as seen in Figure 9.

Obviously, the volume increase triggers the CHPs to run more during periods that do not violate the EEX threshold. Therefore, more thermal energy can be stored in the heat storage even if the heat demand is met. Then, this additional heat is used later when heat is required and EEX prices are lower than the threshold. Thus, TES can be discharged. Additionally, it is significant to underline that this volume increase reduces the boilers' operation to a minimum.

Furthermore, the numerical results indicate that more storage volume yields effective and feasible operation of the heating plant in total as seen Figure 7 and Figure 8, therefore, it is translated into higher profits as shown in Figure 9.

4 Conclusion

This study was carried out to optimize the operation of a CHP-based DH system. A valid power-based model for DH systems was used. Two promising optimization configurations are selected and tested accordingly.

Firstly, an EEX-price driven control strategy is examined to quantify the economic benefits. The outcomes indicate a slight increase in the profits (see Figure 6). Therefore, a second configuration was also tested in parallel with the aforementioned configuration (EEX-driven control strategy), which is installing additional TES volume. This configuration seems to deliver better results than standing the proposed control strategy alone (see Figure 9).

Moreover, an increase in the profit of 0.55 % (price threshold of 30 €/MWh) in year 2020 is not a strong motivation for the operator of the heating plant to implement the new control strategy. Therefore, it is worthwhile to add some other constraints to the control strategy in order to achieve the economic feasibility. Thus, it is recommended to further constraint the CHPs operation such that if the EEX price is negative, then the boilers run instead.

Future work will focus on inspecting the influence of the proposed control strategy on the DH supply and return temperatures. Therefore, thermo-hydraulic models are needed for this task in order to develop the control strategy further and to determine the optimal storage volume.

5 Acknowledgements

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6 Nomenclature

Symbol	Description	Unit
c	Specific cost	[€/MWh]
C	Cost	[€]
E	Energy (i.e. electrical)	[J]
NP	Annual net profit	[€/a]
P	Power	[W]
Q	Heat	[J]
\dot{Q}	Heat flow rate	[W]
R	Revenue	[€]
t	Time	[s]
V	Volume of the storage tank	[m ³]
Δ	Difference	[-]
η	Efficiency	[-]
Abbreviation	Definition	
DH	District heating	
TES	Thermal energy storage	
CHP	Combined heat and power	
EEX	European energy exchange	
MPC	Model predictive control	

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