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Improving the operation of a district heating and a district cooling network

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Abstract

Ongoing research activities at TU Darmstadt aim at improving the energy efficiency of its Campus “Lichtwiese”. In accordance with the national climate protection goals, CO_2 emissions shall be reduced by 80 percent until 2050 compared to the level of 1990. The district heating and cooling networks and the combined heat and power (CHP) generation play a key role in the university’s energy efficiency strategy. The following components for future development are represented in a thermal model of the campus: (1) The cooling supply is switched from compression to absorption chillers supplied with CHP heat, in order to increase the operating time of the CHP plants, especially in the summer. (2) Thermal energy storage along with a predictive control algorithm for the operation of the energy system is implemented to increase the flexibility of the energy supply. This approach also allows to increase the operating time of the CHP plants. (3) The district heating network temperatures, currently depending solely on ambient temperatures, can be reduced considering the heat supply temperature inside the buildings. Thereby, the efficiency of the heat distribution is increased and alternative heat sources can be integrated more easily in the future.

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These components are combined in four different scenarios in order to understand their impact on possible CO_2 emissions and primary energy savings compared to the reference scenario. The components can generate significant efficiency gains at reasonable cost and make a contribution to reach the university's climate protection goals.

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Keywords: District heating operation improvement; combined heat and power; heat demand forecast; thermal energy storage; network temperature reduction

Nomenclature

Symbols

f_{CO_2}	Total CO_2 emissions in optimization scenario in t_{CO2}
$CO_{2,gas}$	CO_2 emission factor gas in t_{CO2}/MWh
$CO_{2,grid}$	CO_2 emission factor grid electric power in t_{CO2}/MWh
$\dot{Q}_{NL}$	Thermal network losses in kW
Q_{TES}	Storage heat content in MWh
$\dot{Q}_{TES,in}$	Heat flow charging storage in kW
$\dot{Q}_{TES,out}$	Heat flow discharging storage in kW
$\dot{Q}_{th,CHP}$	Heat generation CHP in kW
$\dot{Q}_{th,boiler}$	Heat generation boilers in kW
$\dot{Q}_{th,ME}$	Heat demand mechanical engineering in kW
$\dot{Q}_{th,tot}$	Total heat demand in kW
$P_{el,CHP}$	Electric power generation CHP in kW
$P_{el,grid}$	Grid electric power demand in kW
$P_{el,tot}$	Total electric power demand in kW
t	Point in time in hours
Δt	Time step for simulation (1 hour)
T_g	Ground temperature in °C
$T_{amb,thr}$	Heating threshold ambient temperature in °C
T_S	Network supply temperature in °C
η_{TES}	Storage efficiency
$\eta_{tot,CHP}$	Total efficiency CHP
$\sigma_{P,CHP}$	CHP coefficient

Abbreviations

4GDH	4th Generation District Heating
CHP	Combined Heat and Power
HPS	Heat and Power Station
TRY	Test Reference Year

1. Introduction

In order to reach climate protection goals, energy transition and efficiency must not only be tackled on a national, but also on a local level, especially for building heating and cooling purposes. District heating and cooling will play a major role in local energy efficiency strategies in the future, because they are able to connect heat sources and sinks over greater distances, e.g. industrial plants emitting waste heat and residential buildings with heat demand [1]. In order to prepare district energy systems for future changes in energy supply as well as demand, the networks have to be transformed to 4th Generation District Heating (4GDH) as defined in [2]. The idea of 4GDH is to improve the possibility to integrate fluctuating, decentralized and low-temperature heat sources into a district heating system, such as renewable sources or waste heat from industry or data centers. Therefore, network temperatures have to be lowered [3], thermal storage has to be implemented [4] and intelligent control strategies have to be developed [5]. In this paper, we use the case of TU Darmstadt's Campus "Lichtwiese" to evaluate components that make it possible to transform an existing district energy system to 4GDH. We set up four scenarios to compare the impact of the different components in terms of CO_2 emissions and primary energy input to the reference scenario of the 2016 state of the system.

2. The TU Darmstadt Campus Lichtwiese district heating and district cooling networks

TU Darmstadt's Campus Lichtwiese is a typical university campus erected on the outskirts of Darmstadt in the 1960s and expanded repeatedly. In 2016, it comprised 40 buildings with a total net internal area of more than 200000 m^2 for lecture halls, offices, laboratories, workshops and auxiliary buildings, such as a dining hall and the university heat and power station (HPS). Most buildings were constructed in the 1960s and 1970s, but in recent years, construction activity has increased again and several modern buildings with low energy and temperature demand were added. As of 2016, heat for the campus is supplied using three gas engine combined heat and power (CHP) plants (2 $\mathrm{MW_{th}}$ each) as well as six gas boilers (9.3 $\mathrm{MW_{th}}$ each). The CHP plants also provide electric power (1.9 $\mathrm{MW_{el}}$ each) and generate about 60 % of the electric energy needed at the university. In 2017, the campus energy system was expanded by the construction of a district cooling network.

Currently, an absorption chiller (1 MW) and an additional CHP plant (3.3 $\mathrm{MW_{el}}$ / 3.0 $\mathrm{MW_{th}}$) as well as thermal storage are under construction. The campus heat demand is about 23 GWh/a, its electric energy demand 32 GWh/a and its cooling demand 18.5 GWh/a.

TU Darmstadt owns a district heating system with a total length of 28 km, 6.5 km of which connect Campus Lichtwiese (Fig. 1). The district heating supply temperature varies between 65 °C and 110 °C, the return temperature between 45 °C and 75 °C. The new district cooling network operates with a supply temperature of 6 °C and a return temperature of 12 °C. The HPS situated on Campus Lichtwiese does not only supply the campus itself with heat and power, but also other university sites and additional public buildings in the city center of Darmstadt. District cooling on the other hand is only available on campus.

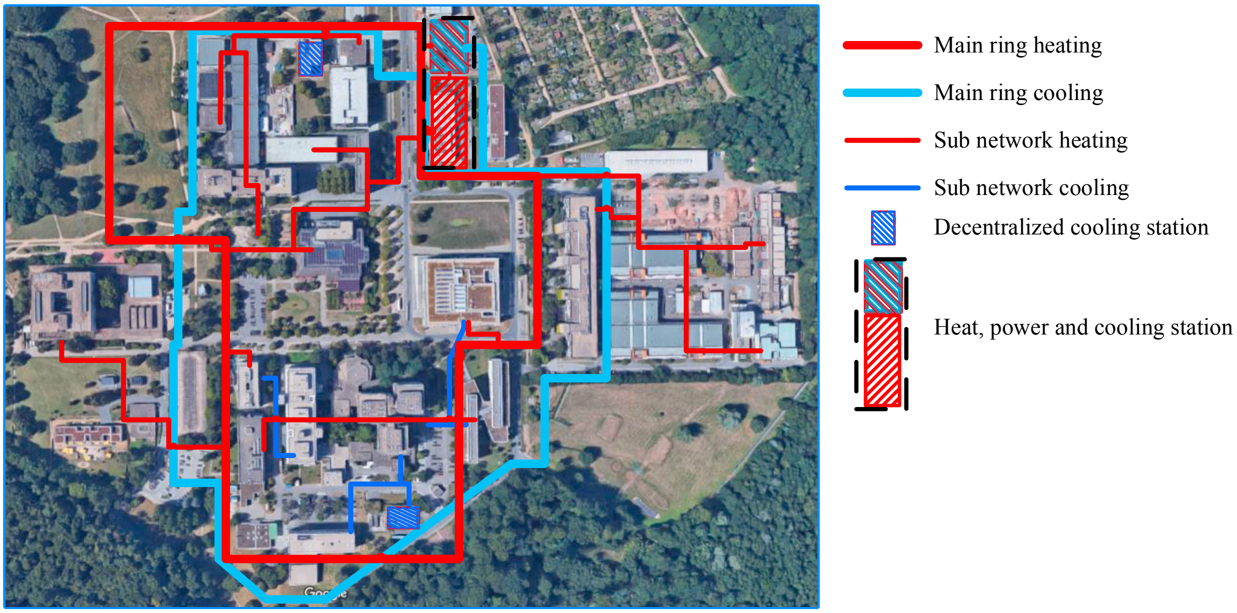

Fig. 1: Campus Lichtwiese District Heating and District Cooling network (adapted from Google Maps)

3. Modeling approach and energy demand profiles

To quantify the impact of possible future adaptations in the energy system, we develop a model of Campus Lichtwiese including heating and cooling generation as well as networks. For modeling purposes, we use MATLAB/Simulink including the CARNOT Toolbox [6].

3.1. District heating model input data

On the heating side, the model serves to calculate network heat losses, temperature distribution across the network, and primary energy input as well as CO_2 emissions to supply the necessary heat and power. Since we focus on the generation and distribution side of the system, we do not include physical representations of the buildings but rather use hourly heat demand and return flow temperature profiles of each building as model input. Additionally, we use the network supply temperature at the HPS. We calculate the hydraulic losses within the network. The losses in the network itself are small compared to the losses inside the buildings where heat exchangers and room heaters generate the main part of the hydraulic losses. Therefore, we use the literature value of 0.5 % of the building heat demand [7] to account for the electric power demand of the network pump that results from hydraulic losses.

3.2. Standardized profiles for building heat demand and return flow temperatures

Heat demand and return flow temperatures depend on weather conditions, therefore simulation results from different years cannot easily be compared to each other. Accordingly, we transform single year heat demand and temperature profiles to standardized profiles using the test reference year (TRY) weather data [8]. This makes the results of the study independent from weather influences of one specific year. We develop regression models for each building to explain daily heat demand and daily average return temperatures depending on average ambient temperatures. To account for the building heat storage capacity, we consider a weighted ambient temperature including the influence of the three previous days. The regression model we selected is a piecewise function separated at the heating threshold ambient temperature $T_{amb,thr} = 15\ °\mathrm{C}$ (Fig. 2). Above this temperature, heat demand only serves for hot water preparation and does not depend on the ambient temperature anymore. We create different regression models for weekdays and weekends since heat demand patterns slightly differ between these cases. We validate the profiles using them to predict heat demand and temperature profiles for real ambient temperatures and comparing them to the measured data (Fig. 3). The annual average deviation between measurement and model in 2017 is about 2-3 %, depending on the building.

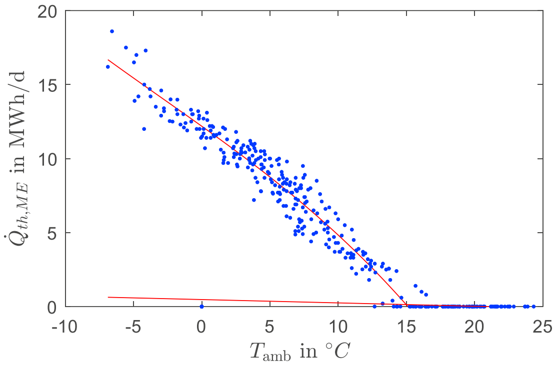

Fig. 2: Regression model for mechanical engineering building

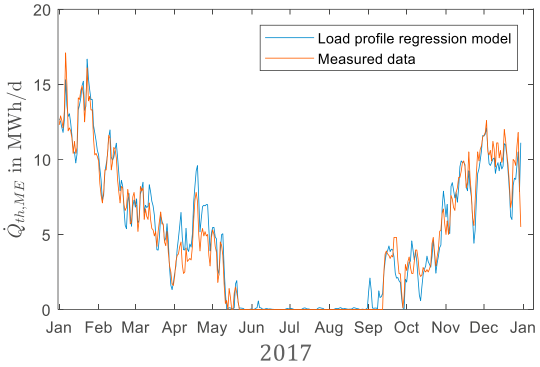

Fig. 3: Regression model validation for mechanical engineering building

3.3. District cooling model input data

Along with the model for the district heating system, we dispose of a model for the district cooling system. We do not yet have detailed information on the cooling demand of individual buildings but rely on one aggregated load profile for the whole campus. The main cooling demand originates from the data center and from experiments in chemical or material research. For the data center, the cooling demand is approximately $\dot{Q}_{cool} = 500\ \mathrm{kW}$. For the other main users, we calculate the cooling demand using supply and return temperatures which are available in the university's building control system. For all remaining buildings, we estimate the cooling demand calculating the impact of internal and external heat sources according to VDI 2078 [9]. We combine all sources available to generate an overall annual load profile for the campus. Considering the fact that detailed cooling load profiles are not available for all buildings, it does not make sense to establish a detailed model of the cooling network representing the physical setup in detail. Instead, we opted for an aggregated modeling approach and do not calculate temperature and mass flow distribution in the network but only cooling energy. We also neglect thermal losses in district cooling as network temperatures are in the range of the ground temperature ($T_g = 10\ °\mathrm{C}$ for Darmstadt) and losses due to heat input into the network are very small. On the other hand, hydraulic losses play a more important role in district cooling than they do in district heating. Due to the same reasons as mentioned for the heating case, also here we consider a literature value of 2 % of the cooling demand [7] as the electric power demand for the district cooling network pump.

3.4. Electric power input data

To account for the overall electric power demand, we rely on measurement data recorded at the transformers on Campus Lichtwiese in 2016. TU Darmstadt electric power bills show that this campus represents about half the university's electric power demand, so we double the measurement data available to account for the total electric power demand we feed into our model.

3.5. Cost calculation

Along with primary energy input and CO_2 emissions, our model is also able to calculate the operational costs of the energy generation. Because costs depend highly on the specific regulatory framework in Germany, we will not present cost related results in this paper.

4. Modeling future network components

We now want to introduce the future network components we investigate to improve the campus energy system. Some of these components are already in the course of implementation; others serve as ideas for future adaptations of the system. In this context, we concentrate on the potential savings of CO_2 emissions and primary energy input in operation. CO_2 emissions and primary energy input to produce new equipment are not considered.

4.1. Summer use of CHP heat via absorption chillers

Centralized cooling via absorption chillers is already in the course of implementation. TU Darmstadt is currently installing a 1 MW absorption chiller that connects heating and cooling generation using CHP heat as its input. This makes it possible to increase CHP heat and power generation, especially in the summer, when formerly heat demand was too low to operate the CHP plants and electric power had to be supplied by the grid. To reflect the system integration, we merge the models for heating and cooling into one combined simulation model. Although absorption cooling provides a significant part of the cooling demand in the future system, compression cooling will keep on playing an important role during wintertime, when the CHP plants are running at full load. Using the absorption cooling machines would mean to use boiler heat for cooling purposes, which is not favorable in terms of primary energy input or CO_2 emissions. Therefore, we consider absorption cooling only when excess CHP capacity is available after supplying the heating demand.

4.2. Integration of a central heat storage

Integrating a central heat storage serves to increase the share of CHP heat and power generation and control the maximum peak in the heat and power plant's gas demand. The storage technology we consider is a stratified sensible water storage, which can store heat at temperatures up to about 150 °C at the network's pressure level (5.3 bar) and at very low cost. In order to investigate the potential of improved operating strategies, we consider a storage volume of 2,200 m^3, which allows storing heat for about 12-24 hours in spring and fall, depending on the heat load demand and the required temperatures. The storage is used to store CHP heat exclusively due to the high efficiency of the combined generation compared to the alternative of grid electric power and boiler heat.

We integrate the heat storage into our system using an intelligent prediction and optimization algorithm. The goal of the optimization is to supply the necessary heat load using the available generation and storage units in a way that minimizes CO_2 emissions. Before we can optimize the system operation, we first need to predict the overall heat load over the time horizon for which we want to create flexibility, in our case 24 hours. A longer horizon would only make sense if we considered a much bigger storage in order to not only disconnect heat supply and demand on a daily basis but also account for differences between weekdays and weekends or even seasonal patterns. If we did not predict the heat demand for our time horizon and were to optimize the system's operation for each point in time individually, the storage would be discharged whenever possible. This would be the optimal solution for each individual step but not the global optimum for a whole day. We carry out the heat load prediction in a separate, simplified and linearized model calculating only heat generation instead of the detailed temperature and mass flow calculation of the main model. Additionally, the prediction model uses a multiple polynomial regression model to account for the network heat losses instead of a detailed simulation of these losses.

In order to be able to find global optima and to reduce simulation time, we apply a linear optimization algorithm. Our objective function states:

$$f_{CO2} = CO_{2,gas} \cdot \frac{Q_{th,CHP}+W_{el,CHP}}{\eta_{tot,CHP}} + CO_{2,gas} \cdot \frac{Q_{boiler}}{\eta_{boiler}} + CO_{2,grid} \cdot W_{el,grid} \qquad [\mathrm{t}_{CO2}] \tag{1}$$

We have to obey the following constraints:

$$\dot{Q}_{th,CHP}(t) + \dot{Q}_{th,boiler}(t) - \dot{Q}_{TES,in}(t) + \dot{Q}_{TES,out}(t) = \dot{Q}_{th,tot}(t) + \dot{Q}_{NL}(t) \quad [\mathrm{kW}] \tag{2}$$

$$P_{el,CHP}(t) + P_{el,grid}(t) = P_{el,tot}(t) \qquad [\mathrm{kW}] \tag{3}$$

$$Q_{TES}(t-\Delta t) \cdot \eta_{TES} + \dot{Q}_{TES,in}(t-\Delta t) \cdot \Delta t - \dot{Q}_{TES,out}(t-\Delta t) \cdot \Delta t = Q_{TES}(t) \quad [\mathrm{MWh}] \tag{4}$$

$$\dot{Q}_{th,CHP}(t) \cdot \sigma_{P,CHP} = P_{el,CHP}(t) \qquad [\mathrm{kW}] \tag{5}$$

$$P_{el,CHP} \leq P_{el,tot} \qquad [\mathrm{kW}] \tag{6}$$

For each hourly time step, we predict and optimize the operation for the next 24 hours, but only use the result for one step and return to do the same exercise again after simulating one step in the main model using the optimization result (receding horizon).

4.3. Decrease of network temperatures

Lowering the district heating network temperatures is the last approach we investigate to improve the Campus Lichtwiese energy system. As stated in numerous publications on 4th Generation District Heating [2,3,10,11], lower network temperatures are the key factor to prepare district heating for a sustainable future. Lower temperatures decrease heat losses in the network itself and, very importantly, make it possible to integrate low temperature renewable heat sources such as solar, geothermal, or waste heat. Waste heat integration from industrial processes or data centers is especially interesting because it saves energy twice, for heating as well as for cooling of the processes considered [12]. Nowadays, such concepts often fail due to a lack of adequate sinks for waste heat with suitable heat and temperature demand. The lower the network temperatures get, the easier it becomes to use a district heating network to distribute heat from alternative energy sources.On the supply side, temperature depends on the temperature demand of the most critical building and can be controlled centrally in the heat and power station. To determine necessary temperatures at Campus Lichtwiese, we compare primary side supply temperatures to secondary side supply temperatures increased by 4 K to account for the necessary temperature difference at the heat exchangers. This comparison reveals that throughout the year, primary side supply temperatures are 5-20 K higher than secondary side supply temperatures at the most critical building even after considering heat exchanger losses and are decreased before reaching the room heaters via a return flow addition. Therefore, even without energetic renovation of the buildings or the installation of new heaters, network supply temperatures could be decreased considerably (Fig. 4). On the return side, preliminary investigations for representative buildings have revealed that building return temperatures could be decreased by 10-15 K with only small adaptations on the heat transfer system inside the buildings. In the context of this study, we consider a return temperature reduction of 10 K for all buildings.

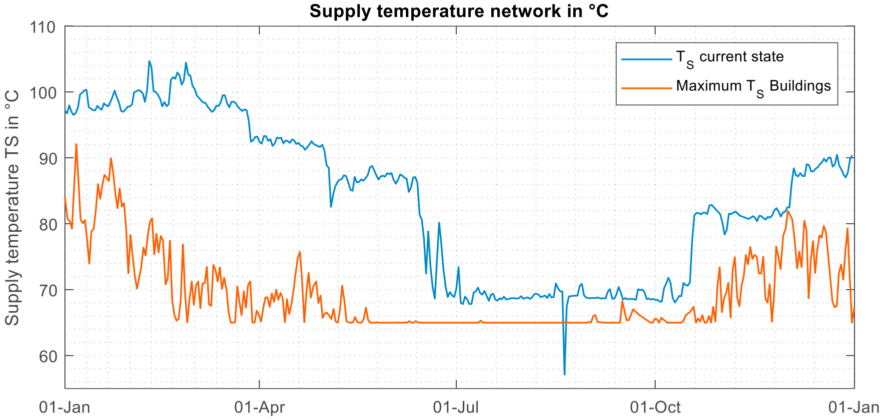

Fig. 4: Comparison of primary and secondary side supply temperatures

5. System adaptation scenarios

To compare the impact of the different future components, we set up five different scenarios:

- Reference scenario: The reference scenario is based on the 2016 campus energy system setup without absorption cooling, thermal storage, unrefurbished CHP plants and high network temperatures (ref)
- Absorption chiller scenario: Fully connected system with new CHP plants and cooling generation based on CHP heat via absorption chillers ($absorp$)
- Temperature reduction: New CHP plants, decreased supply temperatures and exploitation of return flow temperature reduction potential (ΔT)
- TES scenario: New CHP plants and integration of a heat storage as well as application of a predictive optimization algorithm for the operation of the energy system (TES)
- Combination scenario: Combination of all proposed components ($comb$)

Table 1 shows which ones of the future network components are integrated in which scenario:

Table 1. Investigated scenarios

	Old CHP	New CHP	High Temp.	Low Temp.	Absorp. Chiller	TES
ref	X		X			
$absorp$		X	X		X	
ΔT		X		X		
TES		X	X			X
$comb$		X		X	X	X

For the calculation of primary energy input and CO_2 emissions, we use the factors listed in Table 2:

Table 2. Primary energy and CO_2 emission factors

Factor	Value	Source
Primary energy factor grid electric power	1.8	[13]
Primary energy factor gas	1.1	[14]
CO_2 emissions factor grid electric power	0.527 t_{CO2}/MWh	[15]
CO_2 emissions factor gas	0.202 t_{CO2}/MWh	[16]

6. Results and Discussion

As we explained in chapter 1, the HPS supplies heat and power not only to Campus Lichtwiese itself, but also to other sites around the city. In order to model the supply side, we need to consider the entire thermal and electric energy demand of all buildings connected to the district heating system. However, to show the impact of our future components correctly, it makes sense to concentrate on the results for Campus Lichtwiese where they are applied. Therefore, based on simulation results, we calculate the share for Lichtwiese in primary energy input and CO_2 emissions based on the distribution of heat, cooling and electric energy demand between Lichtwiese and the rest of the university energy system. Fig. 5 shows the primary energy savings and Fig. 6 the CO_2 emissions savings for Campus Lichtwiese in the four scenarios we considered compared to the 2016 reference case.

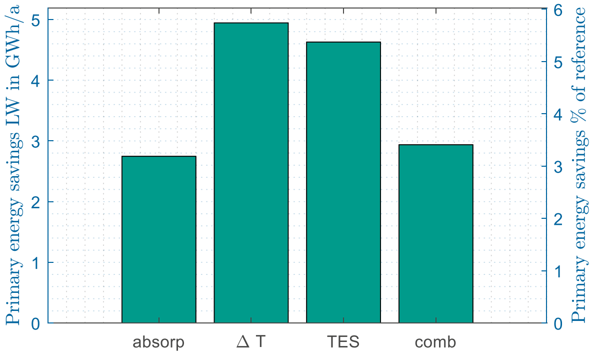

Fig. 5: Comparison of the yearly primary energy input

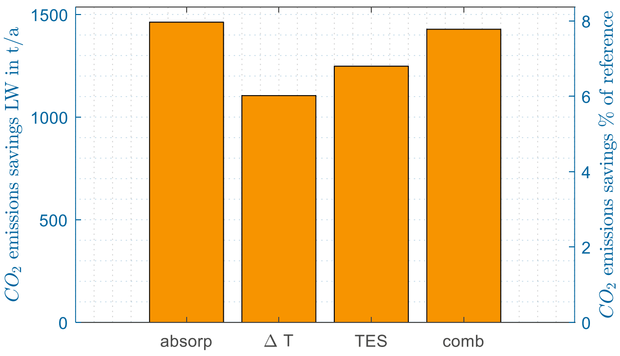

Fig. 6: Comparison of the yearly CO_2 emissions

Uncertainties in the results arise from uncertainties in the input data. We dispose of data on heat demand with a resolution of 100 kWh/h, but we are not able to validate our data appropriately since generation data from our heat and power station is not available. Although data availability on cooling demand is also still limited, this will soon become easier because along with the district cooling ring a more detailed building-wise metering of cooling demand was installed.

The results show that all improvement scenarios allow cutting primary energy input by about 5 % and CO_2 emissions by up to 8 % compared to the 2016 reference case. We now want to take a closer look at the differences between the scenarios. Load profiles presented in this section represent TU Darmstadt as a whole but conclusions drawn from them apply to Campus Lichtwiese equally.

Although reduction potential is quite similar across all scenarios, the strategies applied to improve the system differ, especially between the absorption chiller ($absorp$) and the temperature reduction (ΔT) scenario. The absorption chiller scenario focuses on the integration of new equipment on the generation side to increase the efficiency of the energy supply, while the temperature reduction scenario decreases the heat demand by lowering network temperatures. The

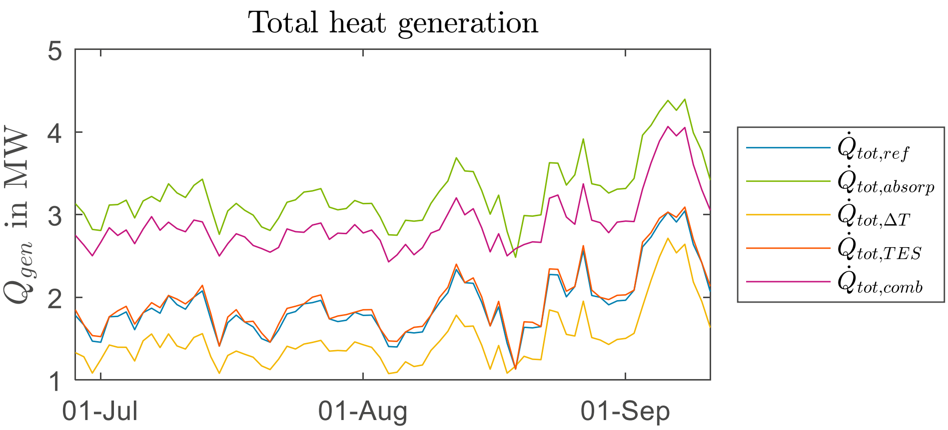

Fig. 7: TU Darmstadt total heat generation July-September

effects of these different approaches become clear when looking at the summer period of the total heat generation (Fig. 7).

In the absorption chiller scenario, heat generation increases compared to the reference scenario due to the additional heat demand for absorption cooling. On the other hand, in the temperature reduction scenario, network losses are decreased and therefore heat generation is lower than in the reference case. We reveal the major disadvantage of the decrease in heat demand due to lower network temperatures in Fig. 8: it leads to a major increase in summer grid electric power demand.

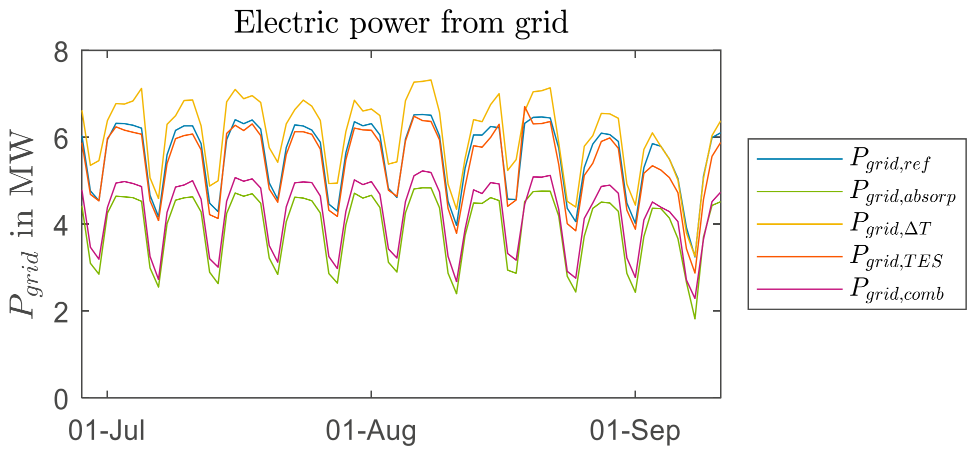

Fig. 8: Grid electric power demand TU Darmstadt July-September

In terms of primary energy input, the temperature reduction scenario is favorable, because the primary energy factor for grid electric power is only 60 % higher than the one for gas (Fig. 5). The CO_2 emissions factor for grid electric power is 160 % higher than the one for gas, so on the CO_2 emissions side, the increased grid electric power demand in the temperature reduction scenario has a lot more of a negative impact (Fig. 6).

In wintertime, the differences are a lot smaller. Absorption cooling is not running because the entire CHP capacity is necessary to supply the district heating demand and network losses represent a much smaller share in the overall heat generation. Therefore, in the winter months, differences between the scenarios in terms of heat generation are almost negligible (Fig. 9).

Storage integration and operation optimization (TES scenario) only have an impact in short periods in the spring and in the fall (Fig. 10). In wintertime, the CHP plants run at full load and no extra capacity is available to store heat. In the summer, heat demand is always lower than the CHP capacity, so the storage remains fully charged.

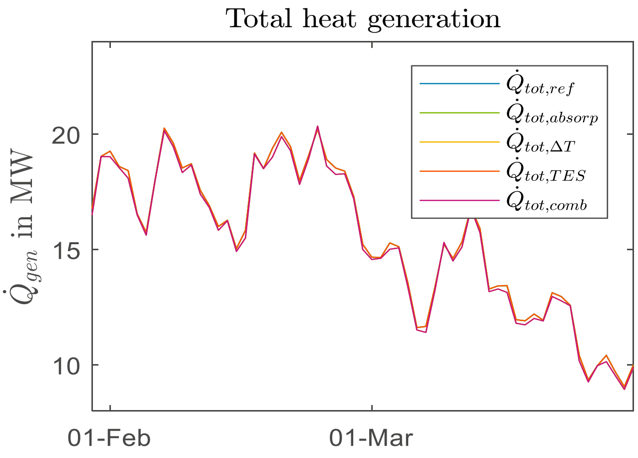

Fig. 9: Total heat generation TU Darmstadt February-March

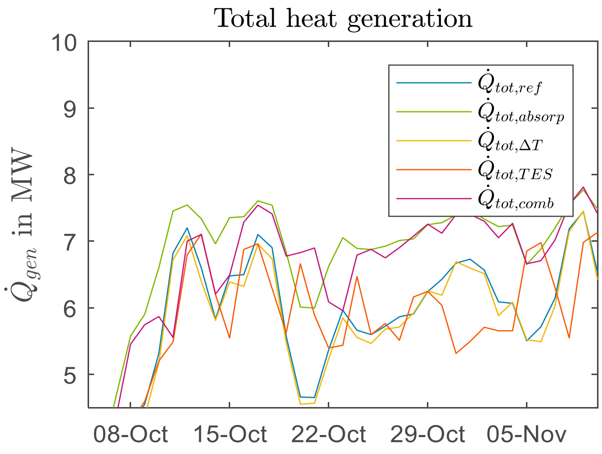

Fig. 10: Total heat generation TU Darmstadt October-November

The results show that we cannot lower yearly gas demand peaks in the current setup of the system. The maximum peak appears in February when the CHP plants already operate at full capacity (Fig. 9). In order to have an impact on the yearly maximum peak, it would be necessary to accept to store boiler heat as well. The results also show that a combination of all future components (combination scenario $comb$) does not lead to the best solution in terms of primary energy input and CO_2 emissions, but rather represents a tradeoff between the previously discussed scenarios due to the effects we just explained (Fig. 5 and Fig. 6).

7. Conclusion and Outlook

The goal of this study was to compare different scenarios to improve the operation of the district heating and district cooling at TU Darmstadt. All scenarios create reductions compared to the reference scenario in terms of the indicators we investigated. Comparing the scenarios among each other, a district heating network temperature reduction leads to lower primary energy input and higher CO_2 emissions while the integration of absorption cooling has the opposite effect. This is due to the major bottleneck in the system: the electric power demand. As long as the electric power demand remains the same, decreases in heat demand will always lead to higher grid electric power demand that generates high primary energy demand and CO_2 emissions. This will only change if the share of renewables in the electric power mix is increased considerably or if electric power demand is decreased on the local level, especially in the summer. We shall also not forget that a network temperature reduction does not only affect heat generation but is a prerequisite for the integration of waste heat and renewables into the system. Future improvements in the system are therefore strongly connected to further reductions in network temperatures.

The model and the simulation results we presented in this paper give us a good understanding of the Campus Lichtwiese energy system. In the future, we will build upon these results and perform sensitivity analyses on key parameters considered as predetermined in this context, such as the heat storage size or the prediction horizon for the optimization. This will make it possible for us to understand if more flexibility through extended storage periods of weeks or even seasonal storage could generate additional benefits. In addition to this, we want use our model to determine the impact of an integration of decentralized heat sources on the system as a whole, such as waste heat from the university’s data center located on campus.

8. Acknowledgement

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References

[1] Bühler F, Petrović S, Karlsson K, Elmegaard B. Industrial excess heat for district heating in Denmark. *Applied Energy* 2017;205:991–1001.
[2] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, Mathiesen BV. 4th Generation District Heating (4GDH). *Energy* 2014;68:1–11.
[3] Rämä M, Sipilä K. Transition to low temperature distribution in existing systems. *Energy Procedia* 2017;116:58–68.
[4] Verda V, Colella F. Primary energy savings through thermal storage in district heating networks. *Energy* 2011;36:4278–86.
[5] Rosemann T, Löser J, Rühling K. A New DH Control Algorithm for a Combined Supply and Feed-In Substation and Testing Through Hardware-In-The-Loop. *Energy Procedia* 2017;116:416–25.
[6] Solar-Institute Juelich of the FH Aachen. *CARNOT Toolbox Version 6.1*; 2016.
[7] Frederiksen S, Werner S. *District heating and cooling*. Lund: Studentliteratur; 2013.
[8] Deutscher Wetterdienst. *Ortsgenaue Testreferenzjahre von Deutschland für mittlere, extreme und zukünftige Witterungsverhältnisse*. Offenbach; 2017.
[9] Verein Deutscher Ingenieure. VDI 2078: Calculation of thermal loads and room temperatures. Berlin: Beuth Verlag; 2015.
[10] Schmidt D, Kallert A, Blesl M, Svendsen S, Li H, Nord N, Sipilä K. Low Temperature District Heating for Future Energy Systems. *Energy Procedia* 2017;116:26–38.
[11] Nord N, Løve Nielsen EK, Kauko H, Tereshchenko T. Challenges and potentials for low-temperature district heating implementation in Norway. *Energy* 2018;151:889–902.
[12] Wahlroos M, Pärssinen M, Manner J, Syri S. Utilizing data center waste heat in district heating – Impacts on energy efficiency and prospects for low-temperature district heating networks. *Energy* 2017;140:1228–38.
[13] Bundesrepublik Deutschland. *Verordnung über energiesparenden Wärmeschutz und energiesparende Anlagentechnik bei Gebäuden: EnEV*; 2014.
[14] Deutsches Institut für Normung e.V. DIN V 18599-1: Energetische Bewertung von Gebäuden. Berlin: Beuth Verlag; 2011.
[15] Umweltbundesamt. *Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix in den Jahren 1990 - 2016*. Dessau; 2017.
[16] Umweltbundesamt. *CO2-Emissionsfaktoren für fossile Brennstoffe*. Dessau; 2016.