Cost Ratio Analysis Evaluating the Potential of an Ice Storage Unit in a Multi-Energy Microgrid

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***Abstract*—As a higher share of electric energy is generated by fluctuating renewable resources, multi-energy systems and their storage capabilities are of growing importance. Quantifying the potential of those multi-energy systems, appropriate analysis tools are required. Due to different energy carriers, new aspects are relevant for analysis. Besides the electricity price, the ambient temperature plays an important role for the optimal scheduling of the components in multi-energy systems with thermal networks. In this paper, a cost ratio analysis is introduced quantifying the potential of an ice storage unit in a cooling supply system. The analysis is applied to a business facility in Berlin comparing a dynamic electricity price and a carbon emission based price. The resulting cost ratios show the differences in beneficial usage times for both price signals at diverse days. A heat map is proposed to evaluate the performance.**

***Index Terms*—multi-energy system, smart grid, microgrid, ice storage unit, cooling network, demand side management.**

Nomenclature

a_{co}, a_{ice}, b_{co}, b_{ice}	Parameters of linearized chiller model.
c_{el}	Electricity price.
C_{el}	Costs for electricity consumption.
E_{cha}	Charge energy of ice storage unit.
E_{dis}	Discharge energy of ice storage unit.
$E_{\text{chi,co}}$	Cooling energy produced by chiller.
$E_{\text{chi,ice}}$	Ice energy produced by chiller.
$E_{\text{chi,el}}$	Electrical energy consumption of chiller.
$E_{\text{ld,co}}$	Cooling demand.
k	Number of time steps.
$P_{\text{chi,co}}$	Cooling power produced by chiller.
$P_{\text{chi,ice}}$	Ice power produced by chiller.
$P_{\text{chi,el}}$	Electrical power consumption of chiller.
t_n	n-th point in time.
Δt	Time step size.
T_n	Time period between $t_n - \Delta t$ and t_n.
$T_{n\text{-}k}$	Time period between $t_{n\text{-}k} - \Delta t$ and $t_{n\text{-}k}$.
η	Overall efficiency of ice storage unit.
η_{cha}	Charge efficiency.
η_{dis}	Discharge efficiency.
η_{sd}	Self-discharge efficiency per day.
ϑ_{a}	Ambient temperature.
χ_{el}	Cost ratio.
χ_{CO_2}	Carbon emissions ratio.

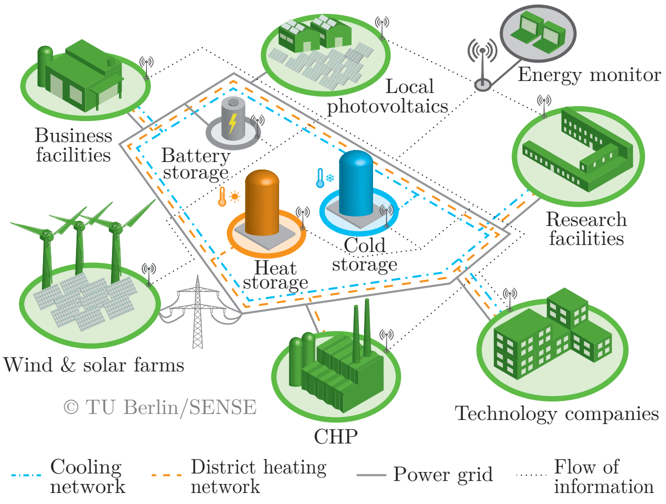

Fig. 1. Scheme of a multi-energy microgrid.

I. Introduction

Due to the rising share of fluctuating renewable resources in power systems [1], flexible loads and storage devices are increasingly demanded [2], [3]. In this respect, multi-energy systems combining electricity grids with thermal networks become of significant interest [4], [5]. An example for a multi-energy system including district heating and cooling networks is illustrated in Fig. 1. The storage devices of these networks allow the decoupling of thermal power generation and demand.

In [6]–[9], different approaches for the optimal scheduling of thermal generation and storage units are given. The consumed electrical energy and the costs are compared for various electricity prices. Besides the comparison of the electricity prices, the usage of renewable energy generation is analyzed in [10]. In all these studies, the total operational costs for the considered time intervals are calculated. In addition to that, a detailed analysis of the times of usage would be valuable. This enables to quantify the benefit for each time period of storage unit operation.

In this paper, a comparative investigation of two cooling supply alternatives by a cost ratio analysis is proposed. The base case, where the cooling power is generated at the time of demand, and a time-decoupled supply through an ice storage

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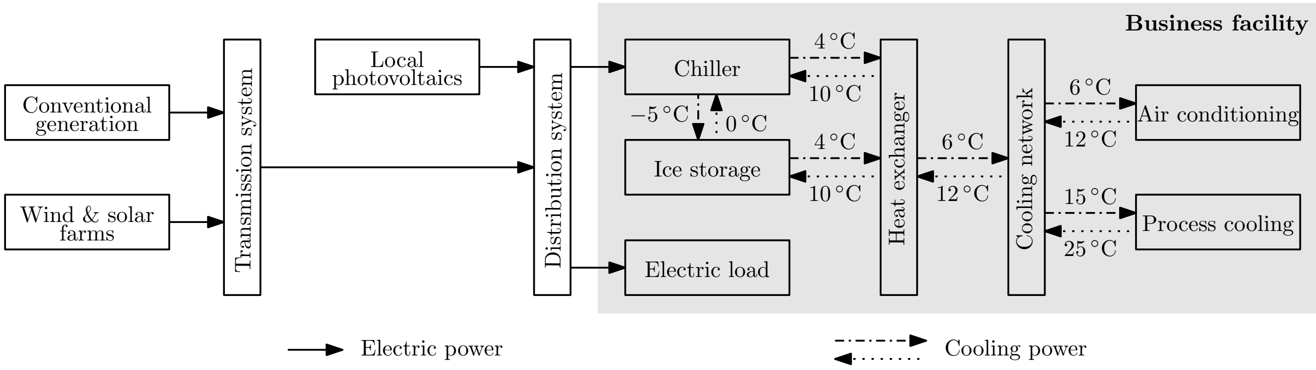

Fig. 2. Block diagram of multi-energy system with cooling supply system.

unit are compared. The presented approach allows to compare different price models with regard to beneficial operation time periods of the chiller. Besides the dynamic electricity price dependent cooling power generation, the analysis is carried out for a carbon emissions optimized operation of the chiller. Moreover, the impact of ambient temperatures and efficiencies of the ice storage unit on the performance is studied.

Following the introduction, a cooling supply system for cost ratio analysis is modeled in Section II. In Section III, the cost ratio analysis is introduced and explained for exemplary parameters. Cost ratio analysis is applied to the use case of a business facility in Berlin Adlershof in Section IV. Conclusions can be found in Section V.

II. Modeling of Cooling Supply System for Cost Ratio Analysis

A multi-energy system as shown in Fig. 2 is considered. In particular, the cooling supply system of the business facility, containing chiller and ice storage unit, is focused on. Air conditioning and process cooling appear as the cooling loads in this system. The system operation is affected by the electricity price. The chiller, which consumes electrical power while generating cooling power, can be operated with regard to the electricity price. Satisfying the demand during this operation mode, an ice storage unit is involved. For both components, ice storage unit and chiller, models for the analysis of operation are presented in the following.

The electrical power consumption of the chiller depends not only on the cooling demand, but also on ambient temperature and flow temperature. As a function of the flow temperature, two operation modes of the chiller are feasible. In operation mode “cool”, the temperature of the refrigerant is $+4$ °C. In operation mode “ice”, the refrigerant is cooled down to -5 °C. This operation mode leads to a higher electrical power consumption of the chiller than it is the case for operation mode “cool”.

The relation of electrical power consumption and thermal power generation can be modeled by different approaches [11]–[13]. Here, a linear regression model, as presented in [12], is applied to the two operation modes. The linear model

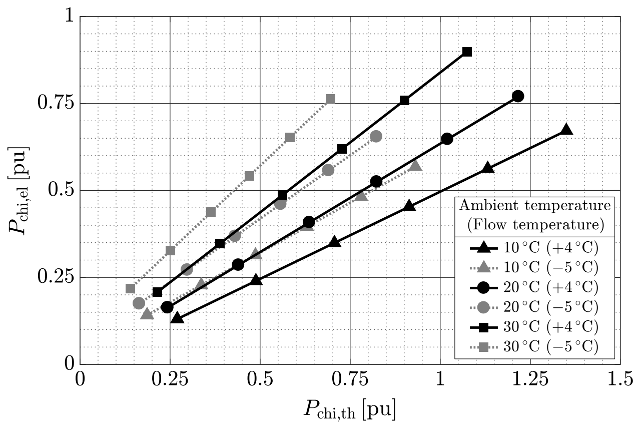

Fig. 3. Linearized load profiles of a compression chiller.

is parametrized based on data sheet [14] and measurements. Therefore, electrical power consumption $P_{\mathrm{chi,el}}$ and thermal power generation $P_{\mathrm{chi,co}}$ and $P_{\mathrm{chi,ice}}$ for the two operation modes “cool” and “ice” are related as follows:

$$P_{\mathrm{chi,el}}(t) = a_{\mathrm{co}}(\vartheta_{\mathrm{a}}(t)) \cdot P_{\mathrm{chi,co}}(t) + b_{\mathrm{co}}(\vartheta_{\mathrm{a}}(t)) \quad (1)$$

$$P_{\mathrm{chi,el}}(t) = a_{\mathrm{ice}}(\vartheta_{\mathrm{a}}(t)) \cdot P_{\mathrm{chi,ice}}(t) + b_{\mathrm{ice}}(\vartheta_{\mathrm{a}}(t)) \quad (2)$$

where a_{co} and a_{ice} determine the slope, b_{co} and b_{ice} determine the y-intercept of the load profiles. These parameters are dependent on the ambient temperature ϑ_{a}. For selected ambient temperatures, the resulting linearized load profiles are presented in Fig. 3. They are shown for the flow temperatures of both operation modes. The chiller is designed to generate 1 pu of thermal power $P_{\mathrm{chi,th}}$ at an ambient temperature of 35 °C. Under this condition, it consumes 1 pu of electrical power. At lower ambient temperatures, the chiller operates more efficient. Therefore, $P_{\mathrm{chi,th}}$ may exceed 1 pu.

The chiller generates thermal power during different time periods if the cooling demand $E_{\mathrm{ld,co}}$ during time period T_n is directly supplied or if it is supplied through an ice storage unit. Here, T_n is defined as the period between the time points $t_n - \Delta t$ and t_n. Integrating the ice storage unit, the chiller operates during $T_{n\text{–}k}$, i.e. k time periods before thermal power is demanded. The period $T_{n\text{–}k}$ is between $t_{n\text{–}k} - \Delta t$ and $t_{n\text{–}k}$.

During a time period T_n, the electrical energy consumption of the chiller $E_{\mathrm{chi,el}}$ producing cooling energy $E_{\mathrm{chi,co}}$ is according to (1):

$$\begin{aligned} E_{\mathrm{chi,el}}(T_n) = a_{\mathrm{co}}(\vartheta_{\mathrm{a}}(T_n)) \cdot E_{\mathrm{chi,co}}(T_n) \\ + b_{\mathrm{co}}(\vartheta_{\mathrm{a}}(T_n)) \cdot \Delta t \end{aligned} \tag{3}$$

For direct cooling, the produced cooling energy $E_{\mathrm{chi,co}}$ equals the cooling demand $E_{\mathrm{ld,co}}$. Thus, (3) becomes:

$$\begin{aligned} E_{\mathrm{chi,el}}(T_n) = a_{\mathrm{co}}(\vartheta_{\mathrm{a}}(T_n)) \cdot E_{\mathrm{ld,co}}(T_n) \\ + b_{\mathrm{co}}(\vartheta_{\mathrm{a}}(T_n)) \cdot \Delta t \end{aligned} \tag{4}$$

If the ice storage unit is applied, the chiller produces energy $E_{\mathrm{chi,ice}}$ during $T_{n\text{–}k}$. Following (2), the electrical energy consumption of the chiller results in:

$$\begin{aligned} E_{\mathrm{chi,el}}(T_{n\text{–}k}) = a_{\mathrm{ice}}(\vartheta_{\mathrm{a}}(T_{n\text{–}k})) \cdot E_{\mathrm{chi,ice}}(T_{n\text{–}k}) \\ + b_{\mathrm{ice}}(\vartheta_{\mathrm{a}}(T_{n\text{–}k})) \cdot \Delta t \end{aligned} \tag{5}$$

As chiller and ice storage unit are located nearby, the produced $E_{\mathrm{chi,ice}}$ is equal to the charge energy E_{cha} of the ice storage unit. Neglecting losses of the cooling network, the discharge energy E_{dis} is equal to the cooling demand $E_{\mathrm{ld,co}}$.

$$E_{\mathrm{chi,ice}}(T_{n\text{–}k}) = E_{\mathrm{cha}}(T_{n\text{–}k}), \tag{6}$$

$$E_{\mathrm{ld,co}}(T_n) = E_{\mathrm{dis}}(T_n) \tag{7}$$

The relation between $E_{\mathrm{dis}}(T_n)$ and $E_{\mathrm{cha}}(T_{n\text{–}k})$ is determined by the overall efficiency of the ice storage unit $\eta(k)$:

$$E_{\mathrm{dis}}(T_n) = \eta(k) \cdot E_{\mathrm{cha}}(T_{n\text{–}k}) \tag{8}$$

The overall efficiency is composed of the efficiencies at charging η_{cha} and discharging η_{dis} as well as of the self-discharge efficiency per day η_{sd}. As the self-discharge losses depend on the time period between charging and discharging, η_{sd} is raised to the power of $\frac{k \cdot \Delta t}{24\,\mathrm{h}}$. This yields:

$$\eta(k) = \eta_{\mathrm{cha}} \cdot \eta_{\mathrm{dis}} \cdot \eta_{\mathrm{sd}}^{\left(\frac{k \cdot \Delta t}{24\,\mathrm{h}}\right)} \tag{9}$$

Considering (6) and (7) and inserting (8) into (5), the electrical energy consumption $E_{\mathrm{chi,el}}(T_{n\text{–}k})$ subject to $E_{\mathrm{ld,co}}(T_n)$ is determined by:

$$\begin{aligned} E_{\mathrm{chi,el}}(T_{n\text{–}k}) = \frac{a_{\mathrm{ice}}(\vartheta_{\mathrm{a}}(T_{n\text{–}k}))}{\eta(k)} \cdot E_{\mathrm{ld,co}}(T_n) \\ + b_{\mathrm{ice}}(\vartheta_{\mathrm{a}}(T_{n\text{–}k})) \cdot \Delta t \end{aligned} \tag{10}$$

Thus, for a given cooling demand during T_n, the electrical energy consumption of the chiller depends on the overall efficiency of the ice storage unit as well as on the ambient temperature during $T_{n\text{–}k}$. In the case of a direct cooling supply without storage, the ambient temperature during T_n remains as the only influential factor. The effects of different ambient temperatures during $T_{n\text{–}k}$ and T_n as well as different electricity prices on the operation of the cooling supply system are discussed in the following section.

TABLE I
PARAMETERS FOR COST RATIO ANALYSIS

Parameter	Value
Charging efficiency η_{cha}	99 %
Discharging efficiency η_{dis}	99 %
Self-discharge efficiency per day η_{sd}	98.5 %
Number of time steps k	12
Time step size Δt	1 h

III. COST RATIO ANALYSIS

For the evaluation of cooling supply through an ice storage unit in comparison to direct cooling supply, the cost ratio χ_{el} is introduced. It is defined as the ratio between the costs for electricity consumption of the chiller C_{el} during $T_{n\text{–}k}$ and T_n, respectively:

$$\chi_{\mathrm{el}} = \frac{C_{\mathrm{el}}(T_{n\text{–}k})}{C_{\mathrm{el}}(T_n)} \tag{11}$$

If χ_{el} is smaller than 1, it is more beneficial to use the ice storage unit. The costs C_{el} are calculated based on the electricity prices c_{el} and the electrical energy consumption $E_{\mathrm{chi,el}}$. Thus, it yields:

$$\chi_{\mathrm{el}} = \frac{c_{\mathrm{el}}(T_{n\text{–}k})}{c_{\mathrm{el}}(T_n)} \cdot \frac{E_{\mathrm{chi,el}}(T_{n\text{–}k})}{E_{\mathrm{chi,el}}(T_n)} \tag{12}$$

Inserting (4) and (10) into (12), the cost ratio for the considered cooling supply system is given by:

$$\chi_{\mathrm{el}} = \frac{c_{\mathrm{el}}(T_{n\text{–}k})}{c_{\mathrm{el}}(T_n)} \cdot \frac{\frac{a_{\mathrm{ice}}(\vartheta_{\mathrm{a}}(T_{n\text{–}k}))}{\eta(k)} \cdot E_{\mathrm{ld,co}}(T_n) + b_{\mathrm{ice}}(\vartheta_{\mathrm{a}}(T_{n\text{–}k})) \cdot \Delta t}{a_{\mathrm{co}}(\vartheta_{\mathrm{a}}(T_n)) \cdot E_{\mathrm{ld,co}}(T_n) + b_{\mathrm{co}}(\vartheta_{\mathrm{a}}(T_n)) \cdot \Delta t} \tag{13}$$

It is composed of the electricity price ratio and the ratio of electrical energy consumption.

In the following, the influence of both parts on the performance of the cost ratio is demonstrated for the example of Table I and a cooling demand of 250 kWh. The ratio of $E_{\mathrm{chi,el}}(T_{n\text{–}k})$ and $E_{\mathrm{chi,el}}(T_n)$ is illustrated in Fig. 4 for different ambient temperatures. The higher the ambient temperature during T_n, the higher is the energy consumption of the chiller during that time period. Thus, the ratio of the electrical energy consumption decreases. For the example of ambient temperatures of 10 °C during $T_{n\text{–}k}$ and 16 °C during T_n, the energy ratio is 1.15. This is indicated by the dashed blue line.

In Fig. 5, the electricity price ratio for different $c_{\mathrm{el}}(T_n)$ and $c_{\mathrm{el}}(T_{n\text{–}k})$ is shown. Assuming an electricity price of 16 ct/kWh during T_n and a price of 12 ct/kWh during $T_{n\text{–}k}$, this ratio results in 0.75.

The resulting trends of χ_{el} for a cooling demand of 250 kWh and different ambient temperatures are presented in Fig. 6. For the above example, the cost ratio χ_{el} is equal to 0.86. Although the electrical energy consumption is 15 % higher when applying the ice storage unit, finally, the electricity costs are 14 % lower than for direct cooling supply without storage. This is due to the lower electricity price ratio with a lower price during $T_{n\text{–}k}$ compared to T_n.

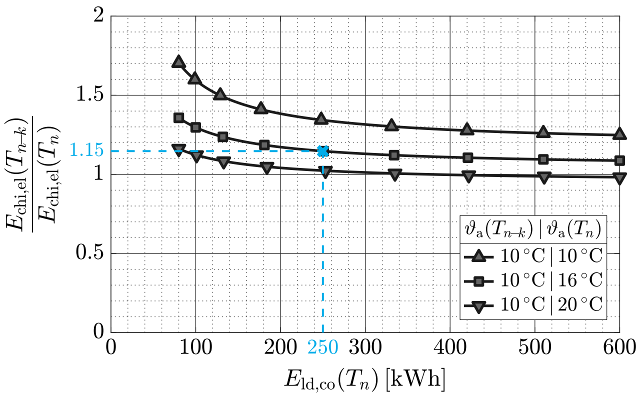

Fig. 4. Ratio of electrical energy consumption versus $E_{\mathrm{ld,co}}(T_n)$ for different ambient temperatures.

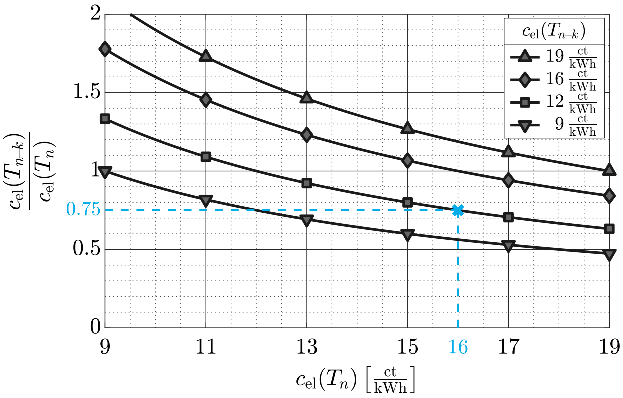

Fig. 5. Electricity price ratio versus $c_{\mathrm{el}}(T_n)$ for different $c_{\mathrm{el}}(T_{n-k})$.

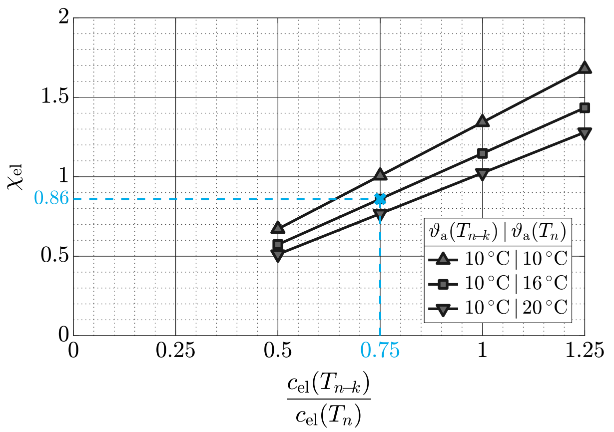

Fig. 6. Cost ratio versus electricity price ratio for different ambient temperatures, a cooling demand of 250 kWh and parameters from Table I.

Analogous to the cost ratio, a carbon emissions ratio χ_{CO_2} is defined. It is constituted as the ratio between the carbon emissions caused by the electricity consumption of the chiller during T_{n-k} and T_n, respectively:

$$\chi_{CO_2} = \frac{CO_2(T_{n-k})}{CO_2(T_n)} \cdot \frac{E_{\mathrm{chi,el}}(T_{n-k})}{E_{\mathrm{chi,el}}(T_n)} \tag{14}$$

TABLE II
CHARACTERISTICS OF EXEMPLARY DAYS

Parameter	Thu, 21.7.	Fri, 18.11.	Mon, 21.11.
Maximum cooling demand $E_{\mathrm{ld,co}}$	760 kWh	280 kWh	220 kWh
Daily ambient temperature spread $\Delta\vartheta_{\mathrm{a}}$	7.6 K	5.4 K	4.0 K
Daily electricity price spread Δc_{el}	1.6 $\frac{\mathrm{ct}}{\mathrm{kWh}}$	6.0 $\frac{\mathrm{ct}}{\mathrm{kWh}}$	4.7 $\frac{\mathrm{ct}}{\mathrm{kWh}}$
Daily carbon emissions spread	0.47 $\frac{\mathrm{kg}}{\mathrm{kWh}}$	0.13 $\frac{\mathrm{kg}}{\mathrm{kWh}}$	0.33 $\frac{\mathrm{kg}}{\mathrm{kWh}}$

IV. Use Case: Business Facility in Berlin Adlershof

The cost ratio analysis is carried out for a business facility in Berlin Adlershof [15]. As presented in Fig. 2, its cooling supply system includes an ice storage unit. The ice storage unit integration into the cooling supply is analyzed for three exemplary days. For the analysis of several days, a heat map as graphical representation is proposed. This allows the comparison of different price signals. Besides the electricity price, a signal based on carbon emissions is evaluated.

A. Input Data

An ice storage unit with efficiencies as listed in Table I is assumed. Fig. 7 shows measurements of cooling demand and ambient temperature as well as the electricity price and the carbon emissions. Key characteristics of the exemplary days are summarized in Table II.

The volatile electricity price is based on the day ahead energy price, published on the ENTSO-E Transparency Platform [16]. Including constant levies and grid charges as well as a trade margin, the electricity price c_{el} varies between 9 ct/kWh and 19 ct/kWh. In addition, [16] provides data classifying generation per production type for each of the four transmission system operators (TSO) in Germany. Berlin Adlershof is located in the area of the TSO "50Hertz". Based on fuel-specific carbon emission factors from [17], the carbon emissions for the control area of "50Hertz" are calculated.

B. Results

Beneficial time periods for a cooling supply with an ice storage unit are shown in Fig. 8. The y-axis indicates the time period T_{n-k} when charging the ice storage unit, whereas the time period T_n is specified by the x-axis. When the cost ratio χ_{el} or the carbon emissions ratio χ_{CO_2} is smaller than 1, the corresponding combination of time periods for charging and discharging is marked in a shade of gray. The darker the marked combination, the more beneficial is the operation of the ice storage unit. Key results are summarized in Table III.

July 21$^{\mathrm{st}}$ is characterized by a large difference in the ambient temperature between morning and afternoon In contrast, the electricity price difference is small. According to the ambient temperature, the cooling demand rises up to 760 kWh. The carbon emissions range from 450 g/kWh in the afternoon to

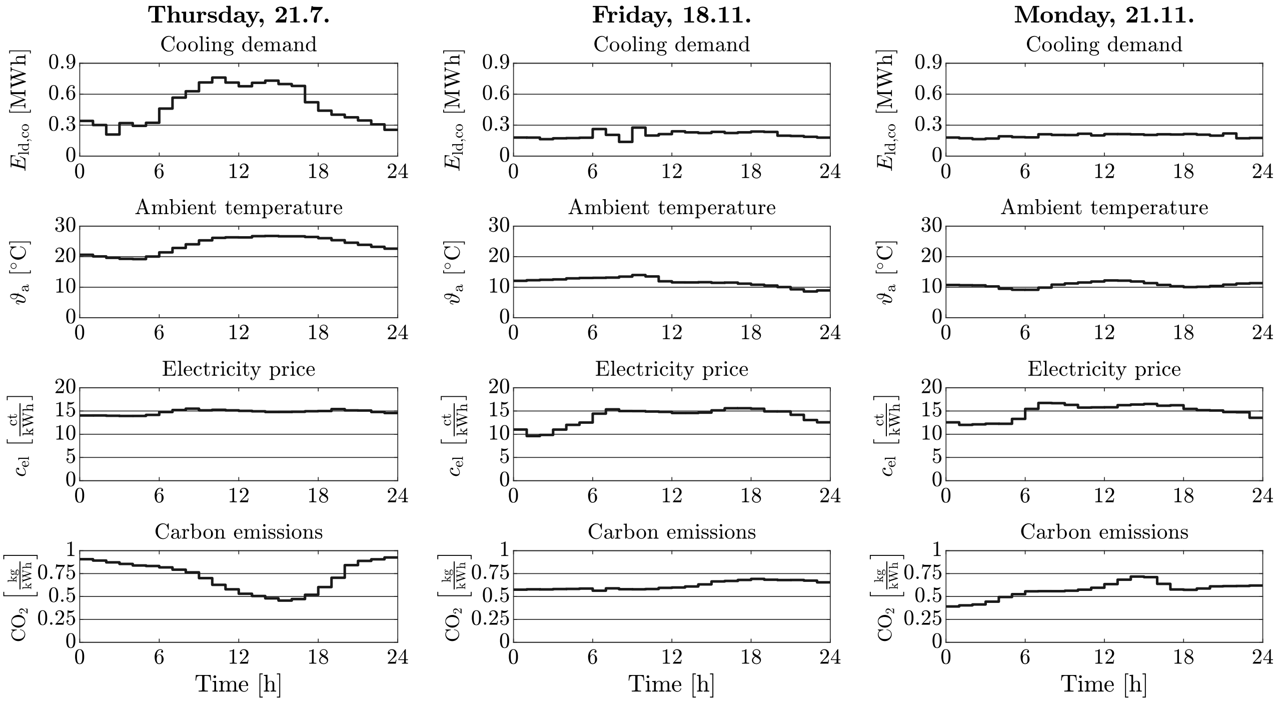

Fig. 7. Use case: Input data at exemplary days in July and November 2016.

TABLE III
COST RATIOS OF EXEMPLARY DAYS

Parameter	Thu, 21.7.	Fri, 18.11.	Mon, 21.11.
Minimum cost ratio χ_{el}	0.97	0.80	0.94
Number of time periods where $\chi_{\mathrm{el}} < 1$	40	45	33
Minimum carbon emissions ratio χ_{CO_2}	0.94	0.93	0.71
Number of time periods where $\chi_{CO_2} < 1$	20	19	70

more than 900 g/kWh at midnight. Operating with regard to the electricity price, 40 profitable combinations of time periods for charging and discharging can be found. The best ratio χ_{el} of 0.97 is attained when the ice storage unit is charged between 4 a.m. and 6 a.m. and discharged between 11 a.m. and 12 p.m. Although the electricity price difference is small in this case, operating the ice storage unit benefits from the high difference in the ambient temperature between morning and afternoon. Considering carbon emissions, there are only 20 beneficial combinations of time periods, but the best χ_{CO_2} is as low as 0.94. In contrast to the electricity price, the carbon emissions are very low in the afternoon, so it is best to charge the ice storage unit between 2 p.m. and 3 p.m. and discharge between 10 p.m. and 11 p.m.

On November 18th, a temperature difference of around 5 K between morning and evening can be observed. Due to the low ambient temperature, the cooling demand varies slightly around 200 kWh with a maximum of 275 kWh. The electricity price difference of 6 ct/kWh is very high, but the carbon emissions only differ by 130 g/kWh. As the electricity price is low during the night, it is proposed to charge between midnight and 4 a.m. After 6 a.m., when the electricity price is much higher, the ice storage unit is to be discharged. In contrast to the wide range of options for discharging considering the electricity price, the nearly constant carbon emission signal leads to very limited beneficial options for discharging.

On November 21st, the temperature difference amounts to only 1.5 K. As on November 18th, the cooling demand varies slightly around 200 kWh. The electricity price rises by around 4 ct/kWh from morning to noon. Its characteristics are similar to the ones on November 18th, but with very different results for the cost ratios. This follows from the fact that the temperature differences are smaller, and the lowest temperatures correlate with a high electricity price. The carbon emissions increase between midnight and afternoon by 330 g/kWh. The high difference in carbon emissions over the day causes the lowest χ_{CO_2} of the three days. If the ice storage unit is charged between 1 a.m. and 2 a.m. and discharged between 3 p.m. and 4 p.m., a benefit of 30 % can be achieved.

At all considered days and for both price signals, there are options for benefiting from using the ice storage unit. Thereby, the absolute values of χ_{el} and χ_{CO_2} vary as well as the number of profitable combinations of time periods.

V. Conclusion

In this paper, a method to determine the potential for the usage of an ice storage unit in a multi-energy microgrid is presented. The ice storage unit is charged by a chiller

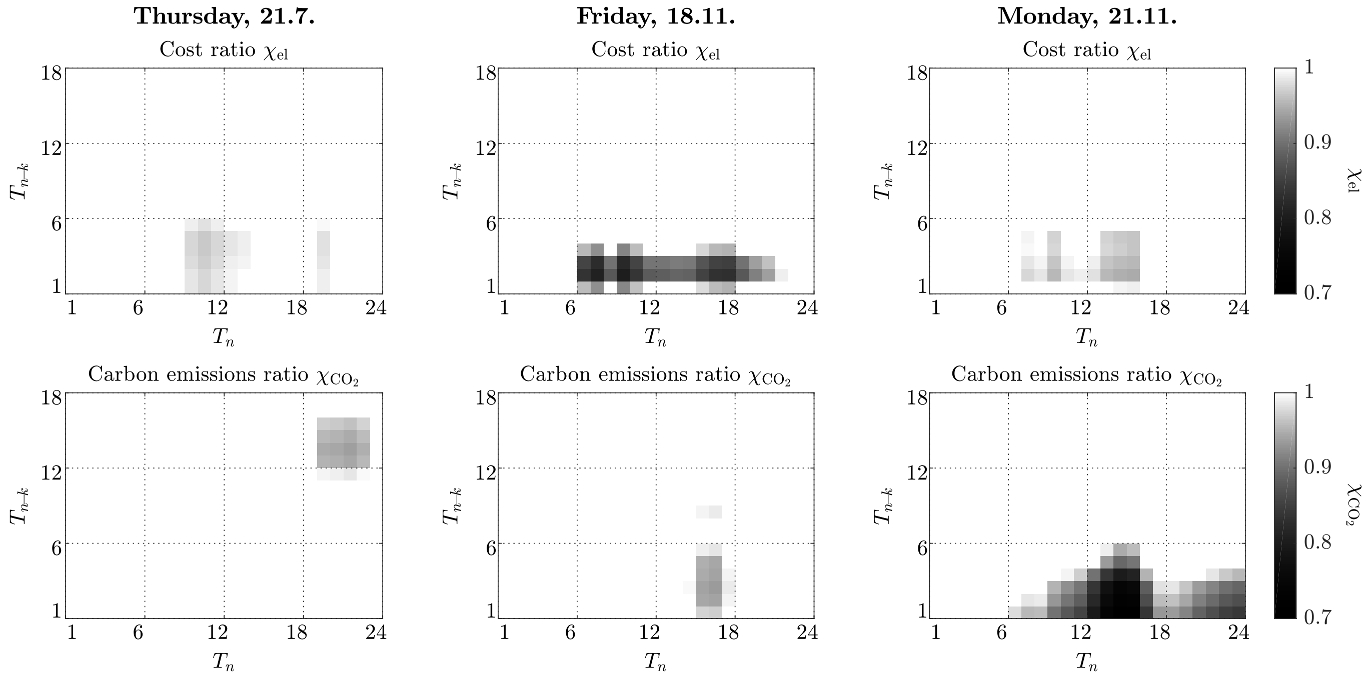

Fig. 8. Use case: Cost ratios for electricity price and carbon emissions at exemplary days in July and November 2016.

consuming electrical power. The electrical power consumption depends on ambient temperature and operation mode. In operation mode "ice", the chiller consumes more electrical energy than in mode "cool". To compare direct cooling supply and cooling supply with ice storage unit, a cost ratio analysis is performed. This analysis is applied to a business facility in Berlin Adlershof comparing a dynamic electricity price and a carbon emissions based price. Three exemplary days in July and November 2016 are studied. It is shown that a high difference in electricity price over a day can lead to a cost benefit of 20 %. Carbon emissions savings of 30 % are achieved for a high daily carbon emissions spread. These results can be well observed by reading the proposed heat map.

Acknowledgment

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