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Evaluation and optimization of the integration of ice energy storage systems in interconnected supply networks for non-residential buildings

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Abstract:

Ice energy storage systems (ICES) in non-residential buildings are a promising technology for utilizing waste heat arising inside the building to efficiently provide heating and cooling without solar assistance. However, there are currently no recommendations for the dimensioning and operation of ICES in interconnected systems with a high level of supply security. Therefore, a detailed numerical investigation of a 500 m³ ICES in a research building is performed and compared with measurement data over one year within this work. Besides, an economic and ecological analysis, a multi-objective evaluation including direct and social costs caused by climate change damages is conducted. An optimization of different operation approaches is examined, ranging from a simple constant operating strategy over a year or representative week, to seasonal control, to an elaborate weekly varying strategy. Moreover, to determine an optimal storage sizing different system combinations are investigated, using a downhill simplex algorithm for each given configuration. Frameworks for Germany, France and EU27 average are used, whereby their influence is investigated by means of a sensitivity analysis. Through an optimized operation, the CO_2 emissions can be reduced by 37 % compared to a conventional system. The adaptation of the plant concept and the determination of an optimal storage dimensioning can also significantly increase the economic feasibility of the realization, whereby a high dependence on the prevailing boundary conditions is evident. The use of ICES leads to an ecological improvement in all regions considered, whereas the methodology can be applied to further building types in the future.

Keywords:

Ice energy storage; thermal storage; heat pump; optimization; dimensioning; non-residential building; waste heat

1. Introduction

The progressive climate change and its negative consequences represent an increasingly important challenge for society, which is why a more sustainable energy supply is unavoidable in all areas. The building sector is currently responsible for 15 % of direct CO_2 emissions from the end-use sector, and in fact, its share of emissions increases to about 30 % if indirect emissions from building electricity and heat consumption are considered [1]. According to the International Energy Agency (IEA), global emissions from space heating are steadily declining while cooling is becoming increasingly important. Thus, appliances and cooling are the fastest-growing uses of energy in buildings, and their growth is expected to continue. In 2019, only 15 % of the energy used for heating was required to meet space cooling demand in the building sector, with about 1 $GtCO_2$ generated through the use of electricity. Nevertheless, based on stated policy intentions, cooling demand is assumed to grow by more than 3 % per year over the next several decades. [2] Beside the higher requirements for air conditioning, especially in non-residential buildings (NRB), there are more and more technical devices like servers that require cooling. Rather than releasing this waste heat unused into the environment and operating refrigeration machines, its utilization represents an auspicious alternative. However, the main challenge is the mostly low-temperature level, complicating the search for technical solutions. [3]

A promising concept is the combined supply of heating and cooling, in which waste heat generated in the building is used directly. Especially NRBs can be suitable for this task, since unlike residential buildings, the demand for cooling does not only occur in the warmer half of the year and often there is even a simultaneous demand for heating and cooling. Nevertheless, Ghoubali et al. [4] show that the important ratio of simultaneous heating and cooling demand is often insufficient even in these buildings due to temporal mismatch. In order to minimize the effects of this time offset, storage systems come into focus.

In this context, especially in recent years, there has been an increase in the amount of research. At this point, borehole systems, which are coupled with a heat pump, are often considered in order to achieve the required high storage capacity. Applications can range from industrial low-temperature waste heat [5] to ice rink and waste incineration [6] to data centers [7]. In the cases mentioned, both ecological and economic improvements can be achieved. However, the common feature of having borehole installations can be a constraint as well. Beside the high investment costs, more and more countries have stricter regulations for drilling, whereby these types of systems could not be deployed at all locations.

A promising extension or even alternative is provided by ice energy storage systems (ICES), which are not affected by any regulations. Contrary to numerous other phase change materials (PCM), water is an affordable alternative that is neither toxic nor flammable, has long-term stability, and offers a high storage density. The first attempts of applying an ice storage for waste heat utilization and simultaneous heat and cold supply already dates back to the year 1980 by Shipper [8]. Recently, for example, Philippen et al. [9] have investigated the use of waste heat from an air ventilation system in a multi-family house. In a previous paper, the use of an ICES entirely without solar support was considered in detail for the first time by Griesbach et al. [10]. In this paper, an ICES with a volume of 500 m³ in a research building and a corresponding numerical model are examined in detail. Over an evaluation period of 13 months, the ICES can provide therein a considerable share of 34 % of the cooling and 31 % of the heating demand. [10]

In an NRB requiring high security of supply, components such as the ice storage and the associated HP are generally integrated in conjunction with other heating and cooling equipment. However, complex mutual reciprocal interactions of the interconnected system complicate the identification of an optimal operating strategy. In addition, there are no recommendations in the literature so far for the dimensioning of the ICES and a prediction on the components which it should be combined with.

At that point this work sets in, whereby this gap should be filled. For this purpose, the existing model of the previous work [10] is supplemented by all generation plants of the compound system and in this context, for the first time, it is investigated as a case study. Over a period of one year (1st October 2020 to 30th September 2021), real plant and consumption data are monitored and compared with numerical results. For this purpose, a numerical model is introduced in MATLAB Simulink [11] with the help of the Carnot component library [12]. In a first step, the detailed numerical model, which considers the complex mutual interactions, is used to investigate the effects of different operating strategies and approaches for optimizing the operation. In addition, various plant configurations are investigated for which an optimal storage system is identified with the application of a downhill simplex algorithm [13]. To evaluate the operation as well as the dimensioning, an economic, an ecological as well as a combined consideration by social costs takes place. The boundary conditions of economic and ecological parameters from different locations on the optimization process are examined and concluded by a sensitivity analysis.

2. Description of the system

Within the framework of this work, a case study is presented, which is located at the Center of Energy Technology (ZET) at the University of Bayreuth in the Technology Alliance of Upper Franconia (TAO) building. From the 5,600 m² of the research building, about 4,000 m² can be attributed to laboratories and workshops. In addition to the heat demand for space heating, the non-residential building has a particularly high cooling demand, which occurs during the whole year. In addition to air conditioning, a high proportion is attributable to laboratory cooling water for machine cooling. Since the building is not connected to any district heating or cooling pipelines, all the required energy is supplied within the building itself. The nominal capacities of all loads and producers are provided in a previous publication [10]. This paper focused on the ice energy storage system and the development of a numerical model, including analytical validation and comparison with long-term measurement data. In the present work, on the other hand, the entire system is considered for the first time, whereby all plants are considered in a combined model.

An overview of the whole system is shown schematically in Figure 1. All heat consumers are supplied by a common heat distribution network, which is supplied by a conventional gas boiler (GB) and gas-fired combined heat and power plant (CHP). The cooling supply of the laboratory cooling water is carried out together with the air conditioning via a common network. As conventional generators, a compression chiller (CC) and the possibility of free cooling (FC) via dry coolers (DC) at low ambient temperatures are installed.

The ICES is located as an innovative interface between these two networks. The heat pump (HP) is able to act as the main heat generator, if its capacity is sufficient to cover the entire demand. In this case, the required flow temperature on the hot water side is set by a mixing valve. If the capacity is not enough, the HP is operated in combination with the GB and/or CHP. Then the HP is used to preheat the return flow of heating water, which reduces the load on the subsequent producers. The source of the HP is the ice storage or the chilled water network directly, the latter assuming that the appropriate heating and cooling demand prevails simultaneously. The ice storage is regenerated via the cold water network, which enables it to provide cooling in a time-shifted

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manner. Since all components interact with each other in a complex way, the entire system is considered in a common interconnected system.

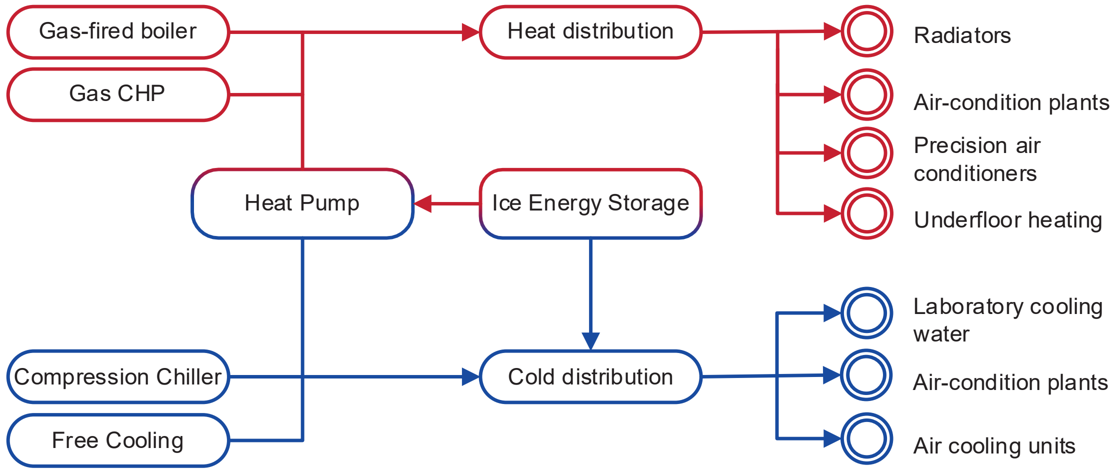

Figure. 1. Simplified scheme of the heat and cold supply system at the University of Bayreuth

A detailed data recording of the entire interconnected system up to the distribution takes place. For this purpose, over 150 data points are continuously logged with a resolution of 1 minute. These comprise all relevant temperatures and flow rates of the respective feed and return lines. The heat meters used are PolluWatt Duo II with an uncertainty of ±0.3 %; PolluStat E with an uncertainty ≤±1.5 % at all producers. At the sub-distribution, 22 PolluStat E are also installed to record in detail the demand of the different consumers. In addition to the provision of load profiles and the analysis of the realized system, the data can be used to validate the numerical models.

3. Methodology

3.1. Formulation of the numerical model

The heating and cooling supply system is entirely implemented in a numerical model in terms of the producers. The simulation environment applied is MATLAB Simulink [11] including the Carnot Toolbox [12]. The components contained therein are mostly adopted unchanged, for instance, the GB, buffer tank according to Patankar [14] and hydraulic components. The models of the HP as well as the CHP are extended by lookup tables, which are parameterized according to the manufacturer's specifications. To determine the electrical power consumption of the DC, the fan characteristic is calculated as a function of the airflow rate. The model of Griesbach et al. [10] is used for the ICES, which has been validated analytically in detail and compared with real long-term measurement data of over one year. Since it is adaptable in terms of dimension, it can also be used in the context of this work to analyse the effects of the dimensioning of the storage.

3.2. Evaluation of the numerical results

The evaluation of the plant operation and dimensioning is performed with regard to economic and ecological criteria as well as a combined evaluation including social costs. The economic consideration is carried out according to the guideline VDI 2067 [15], which combines single as well as recurring payments in a consideration period in a so-called annuity. The recommendation of 20 years is used as the period under consideration. The interest factor q is set at 3 %, the general price increase rate r at 3.1 % and the rate for electric power at 2 %. In addition, the energy tax refund for the CHP and the EEG surcharge of 40 % for self-consumed electricity are applied in the case of Germany. Using the methodology from [15], capital-related costs A_K are calculated including the initial investment and possible residual value as well as replacements. Demand-related costs are determined by the purchase of natural gas $A_{V,gas}$ and electricity $A_{V,el}$ from the power grid. Operating costs A_B include maintenance, inspection and operation of the plants. In addition, other costs A_S such as insurance or taxes can be considered. Proceeds A_E from self-production of electricity are subtracted from the costs. The Chemical Engineering Plant Cost Index (CEPCI) is used to relate the investment costs of the plants to the same reference year [16]. A summary of the costs and parameters used is shown in Table 1.

Table 1. Economic parameters of the heat and cold generators and the ice energy storage [15,17,18].

Component	A_0, €	T_N, yr	n	f_{Inst}, %	f_{W+Insp}, %	f_{Op}, h/a	$CEPCI$
GB	39,598	20	0	1	2	20	2012-2020
CHP	224,298	15	1	6	2	100	2012-2020
CHP (117 kW)	111,913	15	1	6	2	100	2012-2020
HP	60,180	20	0	1	1.5	5	2012-2020
CC	316,428	15	1	2	1.5	1	2012-2020
FC	13,387	20	1	2	1.5	0	2002-2020
ICES	498,031	50	0	1	1	0	2018-2020

In contrast to the established plants, there is no general cost function available for the relatively new technology of ice energy storages. The publication of Allan et al. [19] in which a function for a storage volume of 10 to 270 m³ is contained constitutes an exception. Since within the framework of this work also larger storage systems up to 750 m³ will be considered, an own function based on real costs from the system of the University of Bayreuth will be presented. In order to derive from the realized configuration to others, the so-called six tenth rule [20] with the default value of 0.6 is used. In addition to the storage volume V_{st}, the sum of the pipe length of the charging and discharging circuit l_{CH+DC} can be varied:

$$A_{0,ICES} = 44151 + 134769 \left(\frac{V_{st}}{443\ \mathrm{m}^3}\right)^{0.6} + 152862 \left(\frac{l_{CH+DC}}{6000\ \mathrm{m}}\right)^{0.6} \tag{1}$$

The ecological assessment considers CO_2 emissions from gas $\dot{Q}_{gas}$ and electricity consumption $\dot{Q}_{el,con}$ and power generation by the CHP $\dot{Q}_{el,gen}$. The total emission A_{CO_2} is calculated by means of CO_2 factors for gas $a_{CO_2,gas}$ and electricity $a_{CO_2,el}$ for the respective electricity mix of the grid. Since the entire electricity is self-consumed, a subtraction with the grid factor is performed:

$$A_{CO_2,i} = a_{CO_2,gas,i} \int \left(\dot{Q}_{gas,i}\right) \mathrm{d}t + a_{CO_2,el,i} \int \left(\dot{Q}_{el,con,i} - \dot{Q}_{el,gen,i}\right) \mathrm{d}t \tag{2}$$

The reference cases Germany (DEU), European average (EU27) and France (FRA) are utilized to identify the influence of the boundary conditions on the evaluation and optimization. A summary overview of the parameters applied is given in Table 2.

Table 2. Economic and ecological parameters [21–25].

Location	$A_{V,gas}$, €/kWh	$A_{V,el}$, €/kWh	$a_{CO2,gas}$, g_{CO_2}/kWh_{gas}	$a_{CO2,el}$, g_{CO_2}/kWh_{el}	hr, €/h
DEU	0.0564	0.2016		366	
EU27	0.0613	0.1584	194.3	226	73
FRA	0.0660	0.1099		57	

Frequently, an economic and ecological evaluation might not move in the same direction and may even be contrary to each other. In order to perform a combined evaluation, there is the challenge of applying a non-arbitrary weighting. Therefore, in this work, CO_2 emissions are attributed a price as a consequence of social costs in the form of climate consequential damages a_{clim,CO_2} in accordance with the German federal environmental agency [26]. These can be added to the direct costs of the plant operator, allowing a multi-criteria evaluation to be carried out. Two different values are given for the costs incurred to society by CO_2 emissions in Waldhoff et al. [27]. These differ in terms of the pure time preference rate (PTPR) and thus a weighting between the welfare of current and future generations. With a rate of PTPR of 1 %, only 74 % of the damage for the next generation (30 years) and 55 % of the damage for the generation after that (60 years) is considered. At a rate of 0%, on the other hand, the costs are weighted equally for all generations, resulting in higher values for a_{clim,CO_2}. The recommended values depending on the year under consideration are summarized in Table 3.

Table 3. German federal environmental agency recommendation on climate costs [26].

Year of consideration	a_{clim,CO_2} at PTPR=1 %, $€/\mathrm{t\ CO_2}$	a_{clim,CO_2} at PTPR=0 %, $€/\mathrm{t\ CO_2}$
2020	195	680
2030	215	700
2050	250	765

In order to obtain a combined evaluation parameter, the annuity of the overall system is added to the total CO_2 emissions, which are multiplied by a_{clim,CO_2}.

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3.3. Plant operation optimization

Through the number of the different plants there are 24 possible rank orders of the possible plant operation on the cooling side (CCC) and 6 on the heating side (HCC), illustrated in Figure 2. Since these can be combined together in any desired way, there is a total of 144 possibilities for operating the compound system. The respective aggregate with the highest priority of the rank order under consideration is used first. Should its capacity not be sufficient, or if it is not available, the plant with the next higher priority is activated and further on. Generally, FC can only be enabled at ambient temperatures below 6.6 °C and the CHP at a heat demand of at least 70 % of its nominal capacity. HE CH can only operate at an average storage temperature below 5 °C in order to achieve a sufficient temperature difference to the cold-water network. HE HP is only applicable up to a maximum icing degree of 10 %. The HP can operate up to a degree of icing of 80 % or a minimum inlet temperature on the brine side of -9 °C. No separate restrictions exist for the GB and CC.

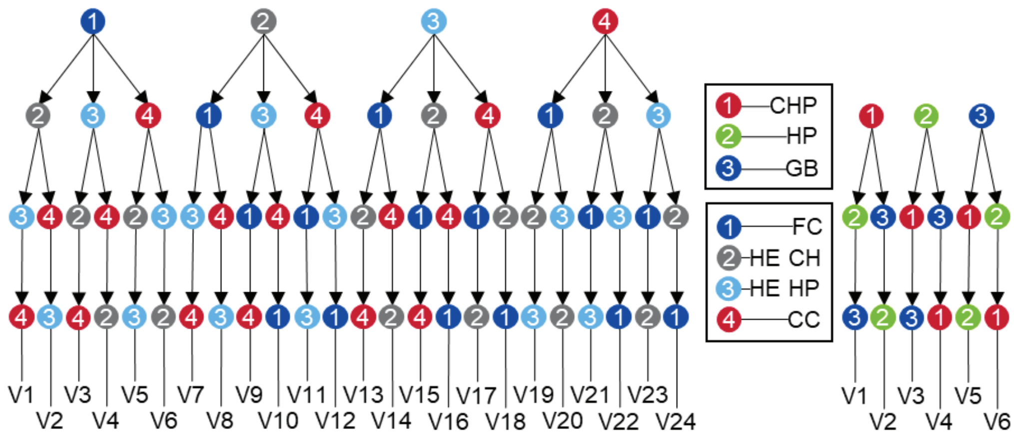

Figure. 2. Possible rank orders of the CCC (left) and HCC (right)

Since mutual interactions exist between the plants and the plant efficiency depends on the state of charge of the storage tank, no simple analytical solution can be formulated for identifying the optimal operation strategy considering all mentioned aspects. Therefore, different numerical optimization approaches to determine an optimal mode of operation are presented and investigated. In Figure 3 these approaches are summarized schematically.

The first and simplest variant is the constant control over the whole year (CCY). For each of the 144 possible combinations, an annual simulation is performed and the best one is selected. Henceforth, this will be enabled constantly over the entire year. In the second variant, on the other hand, only a simulation period of one week is used, i.e. summer (CCS), winter (CCW) and transition (CCT). In order to account for different states of charge of the storage, the model of the storage is initialized with four different degrees of icing. In each case, one week is simulated and the best variant is chosen in the process. Only with the best one a yearly simulation is carried out, which significantly reduces the simulation effort. In the third variant of the seasonal control (SC), an ice-building period $P_{i,b}$ is first defined. During this period, the priority of HE CH is reduced so that the storage is only charged if otherwise the CC has to be activated. The remaining time of the simulation period of one year, the respective strategy is used constantly, resulting in the same effort as for CCY. The best variant is then selected, which needs to be adjusted by the plant operator at the beginning and end of $P_{i,b}$. The fourth variant is the weekly adjusted control (WAC), which is also the most complex one. This is basically equivalent to a model predictive control with a perfect predictive model. Initially, the first week is simulated with all modes of operation and an optimum is selected. The next week is initialized with the final conditions of the previous week and an optimum is identified again. The procedure is repeated until a full year has been examined. For all strategies, both an economical and an ecological objective function can be defined.

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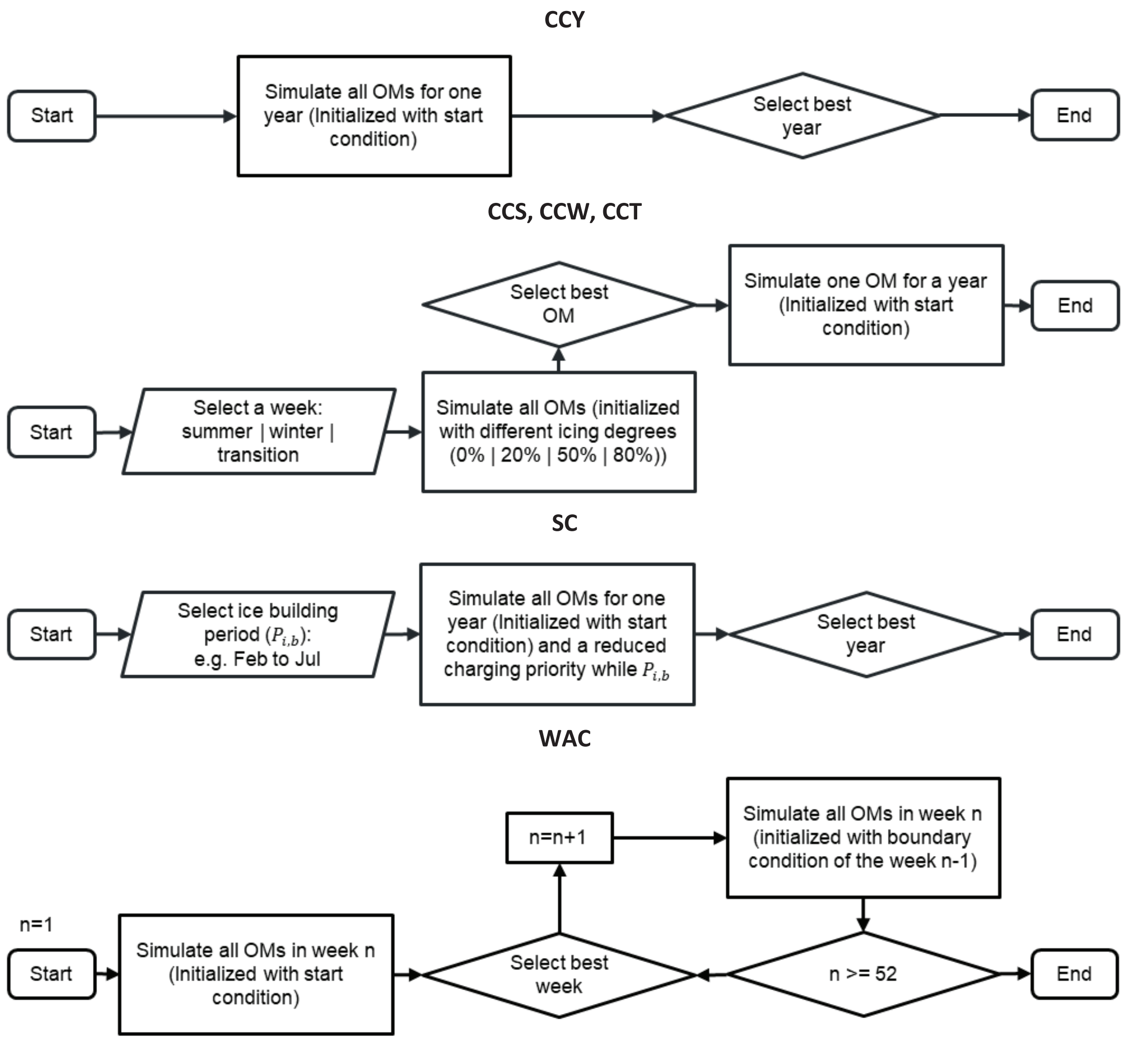

Figure. 3. Flowchart of the CCY (first), CCS, CCW, CCT (second), SC (third) and the WAC (last)

3.4. Plant dimensioning optimization

In addition to the analysis and optimization of the operation of the realized configuration, the influence of different plant dimensioning and configuration is investigated. The focus lies on the ICES here, so the remaining components are dimensioned according to established standard procedures. As the security of supply must be guaranteed, these must be able to cover the complete demand even if the storage tank is completely charged or discharged. Two reference variants (r) are defined and two variants with ICES (I) are considered, which are schematically illustrated in Figure 4. In each variant, the case without (S) and with CHP (C) is considered. FC is used in the S(r) and C(r) cases, whereas it is not applied in S(I) and C(I) in order to utilize as much of the waste heat as possible through the ICES. In the C cases, a CHP with a nominal power of 117 kW is utilized, allowing approximately 4500 full load hours to be obtained. The remaining components correspond to the realization, with the exception of the storage.

With the selected plant concept the dimensioning of the ice storage itself is carried out by a downhill simplex method [13], illustrated in Figure 5. Annual simulations with CCY (HCC: 1 & CCC: 15) are carried out during the optimization. The storage volume as well as the pipe lengths of both hydraulic circuits are continuously varied. The volume is mainly decisive for the storage capacity, which is especially relevant for seasonal considerations. The length of CH essentially influences the achievable regeneration power. The pipe length of DC determines not only the extraction capacity but also the ice layer thickness that forms around the pipes.

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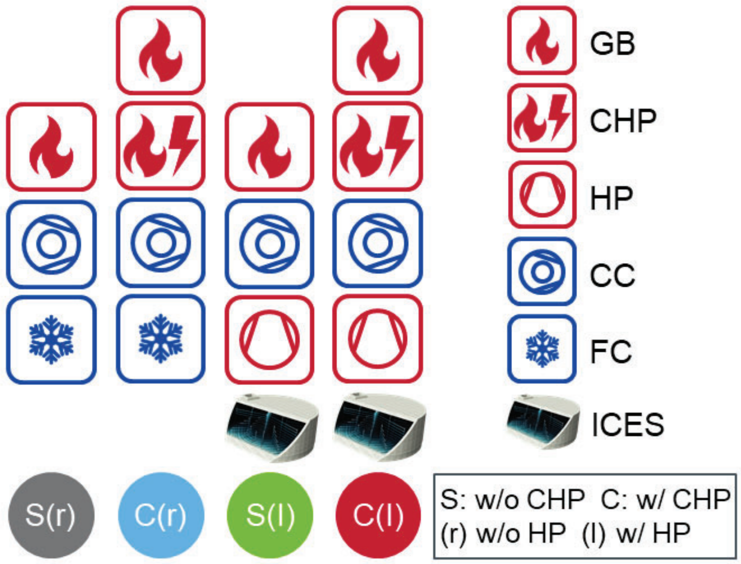

Figure. 4. Schematic overview of the examined combinations

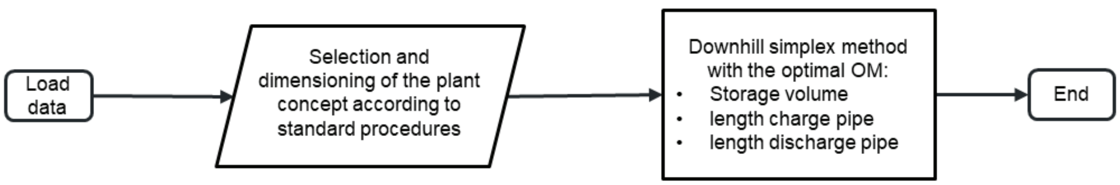

Figure. 5. Flowchart of the dimensioning optimization strategy

4. Results

In this chapter, the results of the plant operation and optimization of the realization concerning the real case study are presented first. Subsequently, different plant dimensions and configurations are investigated, identifying an optimal storage system for each of it. Finally, the chapter concludes with a sensitivity analysis to consider future developments of energy prices and CO_2 emissions of the electricity mix.

4.1. Plant operation

The results of the numerical optimization of the plant operation of the installed system at the TAO building of the University of Bayreuth are presented first. For this purpose, different optimization approaches are presented here instead of all prioritization variants, since especially weekly simulations result in too many variants to present them explicitly at this point. For this purpose, the resulting CO_2 emissions and the annuity for all strategies from chapter 3.3. for an economic (econ.) and an ecological (ecol.) optimization are indicated in Figure 6. The annuity ranges from 212 to 255 k€ and the CO_2 emissions from 148 to 195 metric tons per year.

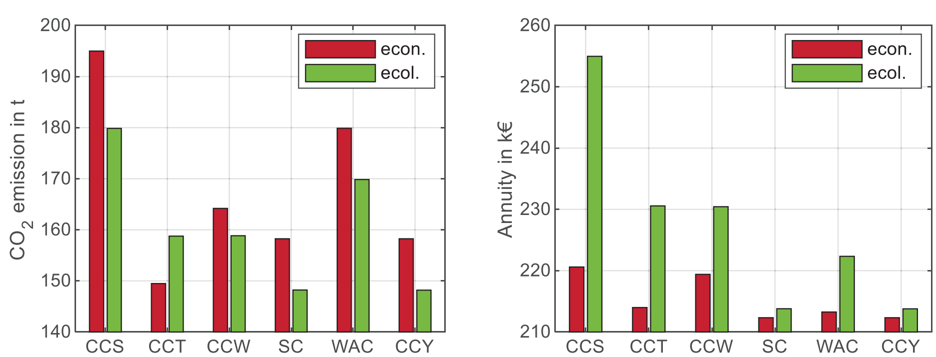

Figure. 6. CO_2 emissions (left) and the annuity (right) of all control strategies considered.

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In general, using CCY yields the best results, however, an annual simulation must be conducted for each strategy to obtain these values. For the CCS, CCT and CCW variants, one week each is simulated with 4 different boundary conditions, resulting in the shortest computation time. Using the summer week in CCS performs worst for both optimization objectives from an economic as well as an ecological point of view. This can be explained by the fact that the full potential of the plant diversity cannot be exploited during this period. The heat demand is not sufficient for the use of the CHP and FC cannot be operated due to too high ambient temperatures. These limitations are not present in CCT, which provides a significantly better representation of potential annual plant usage. With an economic objective function, the ecological and economic optimum from CCY can be met with a distance of less than 1 %. From an environmental point of view, CCW can compete with CCT, while from an economic perspective it is noticeably less competitive. In SC, one annual simulation is also performed in each case, whereby the storage is charged with low priority during the ice build-up period. However, no improvement compared to CCY can be achieved, since in each case a variant is selected in which the ice build-up plays a subordinate role. The main reason stated for this is the complex mutual interactions of the system and the fact that the demand for cooling is relatively constant during the whole year. The last examined variant is the WAC, which is also the most complex one. This corresponds to a model predictive control with perfect prediction with a time horizon of one week. The economic objective function comes close to the optimum of the CCY, but from an ecological point of view it performs considerably worse. An ecological target function is not competitive regarding both evaluation parameters. This can be explained by the fact that for a time horizon of one week, the capacity of the long-term storage is not fully utilized. Due to the fact that the storage tank is not sufficiently cooled during economic optimization, it can hardly provide cold. However, the competitive ability of the system only increases with the combined provision of heating and cooling. In the case of ecological optimization, on the other hand, the CHP is increasingly displaced by the HP as the base load generator, thus noticeably limiting its operating time.

4.2. Plant dimensioning

In the second section of the results, the findings on plant dimensioning according to chapter 3.4. are presented. First, two reference simulations with and without CHP are performed, each with three different boundary conditions. As operating strategies, CCC 15 and HCC 1, which represent the optimum from chapter 4.1, are selected as fixed and non-existing components are omitted. A downhill simplex algorithm is utilized to optimize the storage configuration. The sum of annuity and climate impact costs with PTPR = 0 % is adopted as the objective function of this computationally intensive procedure. Similar to the reference simulations, the boundary conditions for DEU, FRA and EU27 are applied.

The identified optimal storage configuration in dependence of the location, the respective storage volume as well as the determined pipe lengths are listed in Table 1. In the S(I) scenario, the compound system consists of a GB and a CC in addition to the ICES. Using the DEU and EU27 boundary conditions, highly similar storage configurations are determined. In both cases, a significantly longer pipe length is also determined for DC compared to CH. Contrary to the FRA case, an ~5 times larger storage volume is adopted. However, also in this instance, a significantly increased pipe length is identified for CH compared to CH. In conclusion, relatively similar ratios between pipe length and storage volume are selected in all three situations.

In addition to the components from S(I), a CHP is applied in C(I). By means of DEU boundary conditions, a storage volume of 20 m³ is identified, which represents the lowest constraint of the optimization algorithm. Furthermore, a minimum pipe length is chosen, which makes the ICES contribution to the energy supply almost negligible. With the EU27 conditions, a larger storage is chosen than in S(I), whereby the length of CH is hardly shorter than that of DC. The subsequent FRA case identifies a smaller volume that is relatively comparable in scale to the S(I) cases of DEU and EU27.

In conclusion, the prevailing boundary conditions have a considerable influence on the resulting storage. While for S(I) the findings for DEU and EU27 are relatively similar, a significantly larger system is preferred for FRA. The higher investment costs are more rapidly compensated for by savings on the high $A_{V,gas}$ for GB, while the consumption of electricity by HP with low $A_{V,el}$ and $a_{CO2,el}$ is significantly less relevant. In combination with CHP, which represents an additional investment, a smaller ICES is generally identified. In the case of DEU, where CHP electricity generation is highly attractive due to high $A_{V,el}$ and $a_{CO2,el}$ and relatively low $A_{V,gas}$, the contribution by HP is minimized as it displaces the CHP and the additional investment is not viable. In FRA, the ICES advantage may not be as significant due to the CHP as the base load generator, so a significantly small system is identified.

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Table 1. Pipe length and storage volume of all configurations for optimization with the boundary condition DEU, EU27 and FRA

Variant	Location	Storage volume, m³	Pipe length charge, m	Pipe length discharge, m
	DEU	142	562	1047
S(I)	EU27	149	589	1099
	FRA	732	2897	6126
	DEU	20	79	56
C(I)	EU27	213	843	974
	FRA	141	558	1060

A comparison of the annuity and the climate impact costs is presented in Figure 7 for all combinations. The reference case S(r) appears in all regions quite similar, as basically higher $A_{V,gas}$ are compensated by lower $A_{V,el}$ and the investment is equal. In addition, CO_2 emissions and thus the climate impact costs are primarily determined by $a_{CO2,gas}$, a factor that is independent of the location. In C(r), descending competitiveness from DEU over EU27 to FRA is clearly visible. For the annuity, this is largely determined by increasing $A_{V,gas}$ and simultaneously decreasing $A_{V,el}$, making the CHP less profitable. Parallel to this, the climate impact costs also increase due to lower $a_{CO2,el}$, making grid-related electricity savings less attractive. For S(I), the annuity is higher than for S(r), essentially determined by the additional investment of the ICES, which is not compensated by savings in demand-related costs. On the other hand, the CO_2 emissions and thus also the climate impact costs are significantly lower, resulting in benefits in a combined assessment. The most obvious outcome is for FRA, where the investment for the large storage increases the annuity, but minimal climate impact costs prevail at the same time. In C(I), the progression tends to be analogous to C(r) with the same reasons as in this case. For DEU, the annuity turns worse with no decrease in climate impact costs, as the additional investment hardly achieves any changes due to its low contribution. For EU27, the annuity increases while the climate impact costs decrease, yielding in sum similar results as in C(r). Finally, while with FRA constraints an altogether improvement of C(I) over C(r) can be considered, it is not preferable to the S cases, especially due to the highest annuity.

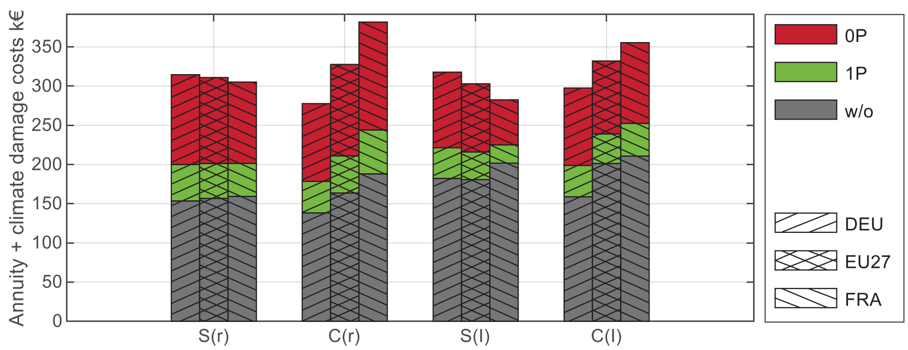

Figure. 7. Annuity plus climate damage costs for all considered regions and configurations.

4.4. Sensitivity analysis

In this last part of the results section, a sensitivity analysis is performed in order to consider the effects of varying boundary conditions. For this purpose, the gas and electricity prices as well as the CO_2 emissions of the electricity mix are varied by ±10 %. The parameter impact on costs or CO_2 emissions is determined according to Saltelli et al. [28] and illustrated in Figure 8. Negative values, as in the C cases, signify that an increase in the input parameter leads to a decrease in the output value.

For S(r), all regions are characterized by a similarly strong dependence on the gas price $A_{V,gas}$. In contrast, the influence of $A_{V,el}$ plays a subordinate role, which decreases slightly with the prevailing value. The influence of $a_{CO2,el}$ is similar, whereas it is almost negligible at FRA due to the low values of the CO_2 emissions of the electricity mix. In C(r), the dependence on $A_{V,gas}$ is reduced compared to S(r), whereas the dependence on the regional price is stronger. On the other hand, due to the self-production of electricity by the CHP, it is possible to benefit from rising electricity prices. As with $a_{CO2,el}$, there is a dependence on the location, which is determined by the respective absolute values. The negative values will increase the CO_2 emissions of the system when $a_{CO2,el}$ decreases due to the expansion of renewable energies in the electricity mix. For S(I), the ICES application results in a decrease in dependence on $A_{V,gas}$ compared to S(r), with an increase in dependence on $A_{V,el}$. However, at the same time, from an environmental point of view, it is also possible to

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benefit from falling $a_{CO2,el}$, which are expected in the future. Finally, the distribution of the impact in C(l) looks similar to C(r). The reduced generation of electricity by the CHP and the increased consumption of electricity by the HP can reduce the impact of $A_{V,el}$ and $a_{CO2,el}$.

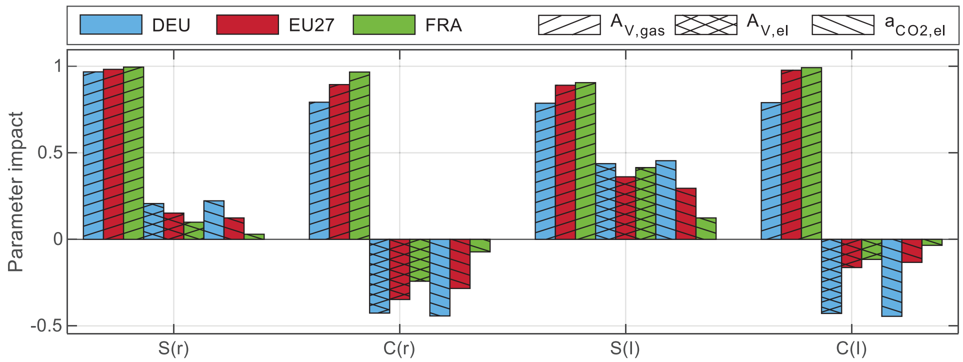

Figure. 8. Parameter impact of the gas and electricity price on the cost and CO_2 emission factor of the electricity mix on the CO_2 emission for all configurations and boundary conditions

5. Conclusion

A detailed numerical investigation of an ICES for the combined supply of heating and cooling energy to a research building is carried out. Therefore, the entire supply system including ice energy storage is implemented in MATLAB Simulink and validated with real long-term measurement data. By means of this, both approaches for the optimization of plant operation and dimensioning can be investigated. To evaluate them, an economic, an ecological as well as a combined analysis with the help of social costs is performed. The optimization of the operation, ranges from a simple constant operating strategy over a year or typical week, to seasonal control, to a sophisticated weekly varying strategy. Moreover, for the boundary conditions of DEU, EU27 and FRA, an optimal storage dimensioning with and without additional CHP is identified using a downhill simplex algorithm. This work is concluded by a sensitivity analysis of the constraints.

Depending on the approach, optimization results for plant operation range from 212 to 255 k€ for the annuity and from 148 to 195 t for CO_2 emissions. The best results can be achieved with a constant operating strategy over the whole year. Whereas computationally efficient weekly simulations are well suited for pre-estimation, neither a seasonal control nor a weekly adjusted strategy with perfect forecasting, both of which are complex to implement, can improve the performance. An ICES can reduce CO_2 emissions noticeably, wherefore an optimal storage is identified within the context of this work, depending on the plant location. Nevertheless, from an economic point of view, a higher annuity must be accepted for systems with ICES due to the additional investment. Combining these with social costs in the form of climate impact damages, an improvement compared to conventional systems can be achieved. Furthermore, the ICES can reduce dependence on natural gas and benefit from the future expansion of renewable energies in the electricity mix.

The approach can be applied in the future to other building types, such as hospitals or office buildings, which are characterized by high heating and cooling requirements. The determining parameters such as the absolute heating and cooling demand as well as the time shift between them should be identified.

Declaration of Competing Interest

The authors declare that there is no conflict of interest.

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Nomenclature

A_0 investment amount, €
A_{CO_2} amount of emitted CO_2, kg
A_V costs of consumed natural gas and electricity, €
a_{clim,CO_2} climate costs, €/t_{CO2}
a_{CO2} CO_2 factor, kg_{CO2}/kWh
hr hourly rate for staff, €/h
l pipe length, m
n replacements, (-)
$P_{i,b}$ ice-building period, (-)
$\dot{Q}$ demand, kW
q interest factor, (-)
R_W residual value, €
r general price change factor, (-)
T observation period, a
T_N service life of the installation component, a
$V_{storage}$ storage volume, m³

Subscripts and superscripts

B operation-related costs
CH charge
con consumption
DC discharge
E proceeds
el electricity
gas natural gas
gen generation
$inst$ repair effort
K capital-related costs
op operating effort
S other costs
V demand-related costs
$W + Insp$ servicing and inspection

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