EVALUATION AND OPTIMAL DIMENSIONING OF ICE ENERGY STORAGE SYSTEMS IN DIFFERENT TYPES OF NON-RESIDENTIAL BUILDINGS

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ABSTRACT

The search for efficient heating and cooling solutions for buildings is becoming increasingly important to counteract the ongoing climate change and rising energy prices. Particularly in non-residential buildings (NRBs), growing amounts of low-temperature waste heat are available but cannot be exploited due to a lack of technical solutions at present. A promising solution is the combined supply of heating and cooling by using this waste heat. However, the time lag between the occurrence of waste heat and demand is an impediment. To balance this mismatch, high capacity thermal storage is required. Ice energy storage systems (ICES) in the absence of solar support are a viable option to utilize this previously unused waste heat in NRBs. Such implementations must be evaluated in the overall context with the remaining generators in the building due to the complex interactions. Moreover, there are currently no standards for the assessment, design and optimized sizing of ICES in NRBs.

For this reason, a detailed numerical evaluation and analysis of an ICES for different building types is carried out in this work. A downhill simplex algorithm is used to optimize plant sizing for various plant configurations with and without a combined heat and power unit (CHP). The evaluation is conducted on a multi-criteria basis, including economic as well as environmental parameters and a combination of both including social costs, under different boundary conditions. In order to systematically consider a wide range of different buildings, the methodology which was carefully tested in an earlier case study is applied to twelve model buildings from eight different use classes. Using simplified preliminary simulations, possibly appropriate candidates of model buildings are determined. Subsequently, detailed variation computations are used to determine an ideal plant and storage configuration.

The optimal configuration of an implementation strongly depends on the prevailing boundary conditions. High gas-to-electricity price ratios and low CO_2 emissions from the electricity mix are generally advantageous for the integration of a storage system. In all investigated regions, the application of an ICES can lead to an environmental improvement of the CO_2 emissions of up to 55 % compared to a conventional system and a reduction of demand-related costs. However, the additional capital investment to integrate an ICES requires rather a high demand for heating and cooling, so the savings in demand-related costs compensate for it. Moreover, at least 8 % of the heating and cooling must occur simultaneously, so the cooling circuit can be used as a straight energy source of the heat pump, allowing the storage tank to be regenerated often. In most cases, pure air-conditioning cannot provide the needed degree of simultaneity, so types of process cooling are essential.

The proposed methodology was tested for twelve building types but can be applied to more building types, like data centers, or to districts with various building types. Especially the combination of the waste heat from NRBs with the heating requirements of residential buildings can decrease the necessary storage capacities and improve the efficiency.

1 INTRODUCTION

The ongoing climate change and rising prices, particularly for fossil fuels, are increasing the relevance of the search for efficient solutions for the building supply. Today, the building sector is accountable for almost a third of global final energy consumption (International Energy Agency 2022) and 37 % of global CO_2 emissions (International Energy Agency 2020a), including both the construction and use

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phases. The International Energy Agency (IEA) estimates that these rates will grow further, as the average annual growth in floor space has continuously exceeded the falling average area-specific energy consumption since 2010 (International Energy Agency 2020c). Besides the provision of heat, the focus is shifting increasingly to the need for cooling, for which the resulting CO_2 emissions almost tripled between 1990 and 2019 (International Energy Agency 2021). Furthermore, space cooling is the fastest emerging end-use for buildings with an annual growth rate of over 3 % during the next three decades, which is eight times higher than the rate for heating over the past 30 years (International Energy Agency 2020b). In addition, particularly in non-residential buildings (NRBs), there are major sources of low-temperature waste heat, e.g., servers or other devices, that are currently not exploited due to a lack of technical solutions (Forman *et al.* 2016). Consequently, there is a need for more efficient solutions to cover both heating and cooling in the building sector, more economically and ecologically.

Combining heating and cooling by using the waste heat generated in the building is a promising concept for reducing the energy consumption. However, (Ghoubali *et al.* 2014) point out the problem of the low ratio of simultaneous heating and cooling demand, that often occurs in buildings due to the temporal discrepancy, hence storage systems have recently received more attention. Additional challenges are the complex interactions within the supply system as well as the waste heat mostly arising at a very low temperature level, limiting the selection of storage materials. Water as a cost-effective phase change material (PCM) is the most advantageous material for latent heat storage from an ecological perspective (Nienborg *et al.* 2018) and, unlike other PCMs, it is cycle-stable, non-toxic, non-corrosive or non-flammable. Based on these crucial advantages, the research of ice energy storage systems (ICES), mainly in the building sector, has become more important in recent years.

The first studies on the combined supply of heating and cooling in a residential building by using the waste heat from a refrigeration system with an ICES were carried out back in 1980 by (Shipper 1980). A small ICES for an apartment building in which, in addition to solar heat, the waste heat from the exhaust air of a ventilation system can be used to regenerate the storage tank is described by (Philippen *et al.* 2018). An ICES with a volume of 500 m³ for the heat and cold supply of a research building is examined in detail together with the development of a corresponding numerical model by (Griesbach *et al.* 2022). In a subsequent study (Griesbach *et al.* 2023b), an optimization of the operation and the system configuration is carried out. To design, evaluate and optimize a combined heating and cooling supply, analyses of the system behavior using variation calculations are essential due to the complex mutual interactions between the different heating and cooling units. For residential buildings with a comparable heating and cooling requirement, manufacturers have empirical values for dimensioning. In contrast, there are no systematic sizing methods in the literature for NRBs, which have widely differing requirements depending on their intended use.

To fill this gap, in this work, the methodology for the optimized realization of an ICES, which was previously carefully tested, is extended and transferred to twelve model buildings. At first, systematically simplified preliminary simulations were performed to identify potential suitable model building types and plant configurations under different boundary conditions. Subsequently, extensive optimization calculations were started for these pre-selected cases only. Afterwards, detailed variational simulations are utilized to determine an optimal plant and storage configuration. Here, a downhill simplex algorithm is employed to optimize the sizing of plants for various configurations with and without a CHP. The evaluation is performed on a multi-criteria basis, involving economic, environmental parameters and a combination of those involving social costs, under various boundary conditions.

2 DESCRIPTION OF THE SYSTEM

In this study, the system configuration from the previous publications (Griesbach *et al.* 2023a, 2023b) is adapted to other building types. The focus lies on a combined heat pump and an ice energy storage system to utilize waste heat generated within the building. The storage serves as the energy source for a brine heat pump (HP), which provides heating. The storage is regenerated by the cold water network, thereby also contributing to the cooling provision. The ICES is supplemented by a gas condensing boiler (GB), a CHP, a compression chiller (CC) and the option of free cooling (FC), as schematically summarized in Figure 1.

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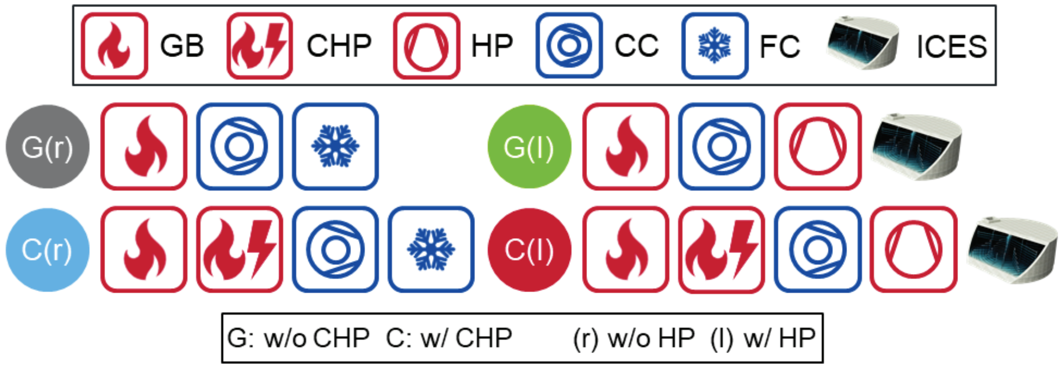

Figure 1: Schematic overview of the examined combinations

A total of twelve different model buildings are applied, assuming a new building in each case. The respective usable building area is taken from the model database according to (Zentrum für Umweltbewusstes Bauen e.V. 2010) and the publication by (Wirtz 2023). The selected buildings represent 57.8 % of the German non-residential building stock in 2021 according to (M. Hoerner *et al.* 2022). In addition, the Green Hospital Lichtenfels (GHL) (Landkreis Lichtenfels im Rahmen einer Kooperation der Technologie Allianz Oberfranken (TAO) 2022) is considered to compare the methodology of calculating synthetic load profiles with real consumption data.

3 METHODOLOGY

3.1 Numerical model

A numerical model is developed for the entire system of the producers of the heat and cold supply. The overall model was presented in a previous publication (Griesbach *et al.* 2023b), in which all components were validated. In addition, an analysis of the operating behavior and the possibility of considering further system dimensioning can be found in it and in (Griesbach *et al.* 2023a). For this purpose, plants from the same product series are approximated by using data sheet values similarly. The ICES is implemented using the model of (Griesbach *et al.* 2022), that has been analytically validated in detail and compared with actual long-term measurements of more than one year. The model is adaptable in terms of dimension, and therefore it can be utilized within this work to study the effects of the storage dimensioning. As simulation environment, MATLAB (The MathWorks Inc. 2020a) and Simulink (The MathWorks Inc. 2020b) including the Carnot Toolbox (Solar-Institut Jülich 2018) are used.

3.2 Evaluation of the numerical results

The plant dimensioning is evaluated based on economic and ecological aspects, as well as a combined evaluation including social costs. The economic evaluation is conducted based on the guideline VDI 2067 (Association of German Engineers 2012), combining single and recurring payments within a consideration period within a so-called annuity. To relate the investment costs of the plants for the same reference year, the Chemical Engineering Plant Cost Index (CEPCI) (Chemical Engineering 2022) is applied. For a summary of the costs and parameters, see (Griesbach *et al.* 2023a, 2023b), which both use the identical values. The cost function presented therein for the ICES is used in the detailed system simulation with the so-called six-tenths rule (Tribe and Alpine 1986) taking the default value of 0.6. For the preliminary simulations, the investment cost function $A_{0,ICES}$ is simplified and used as a function of the heat extraction rate $\dot{Q}_{DC}$ instead of the storage volume and the pipe length of the heat exchanger:

$$A_{0,ICES} = 44{,}151 + 287{,}631 \left(\frac{\dot{Q}_{DC}}{100\ kW}\right)^{0.6} \qquad (1)$$

The environmental evaluation includes CO_2 emissions from gas and electricity consumption and CHP electricity generation, using CO_2 factors for gas and electricity, based on the respective electricity mix of the grid. As the total electricity generated is self-consumed, a subtraction with the grid factor is performed according to (Griesbach *et al.* 2023a, 2023b). There is also an overview of the parameters of the reference cases Germany (DEU), European average (EU27) and France (FRA), that are employed to identify the influence of the boundary conditions on the evaluation and optimization. Moreover, these

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works describe the methodology of assigning a price to CO_2 emissions due to social costs in the form of climate consequential damages according to the German Federal Environmental Agency (Umweltbundesamt 2022). Two different values for the costs incurred to society by CO_2 emissions, which vary regarding the pure time preference rate $PTPR$ and hence a weighting between the welfare of present and future generations, are provided by (Waldhoff *et al.* 2014). To obtain a combined evaluation parameter, the total system annuity is summed with the total CO_2 emissions, which are multiplied by these costs.

3.3 Plant dimensioning optimization

The effects of different plant sizing and configurations are investigated. The main concern in this context is the ICES, so the remaining components are scaled in accordance with established standard procedures. In order to ensure reliability of supply, they have to be sufficient to cover the total demand, also when the storage is fully charged or discharged. Two reference variants (r) and two variants with ICES (I) are considered, as shown schematically in Figure 1. Each variant considers a case without CHP (G) and a case with CHP (C). In G(r) and C(r), FC is added, while in G(I) and C(I), it is left out in order to maximize the use of waste heat via the ICES.

The ice storage is dimensioned using a downhill simplex method (Nelder and Mead 1965) with the selected plant concept. The optimal operation strategy, as determined in a previous publication (Griesbach *et al.* 2023b), is applied consistently. The storage volume and the pipe lengths of the two hydraulic circuits are varied continuously. The water volume defines the storage capacity, which is particularly important for seasonal aspects. The charging circuit length primarily determines the achievable regeneration capacity. The length of the pipes in the discharge circuit affects the extraction power, as well as the thickness of the ice layer that builds up around the pipes.

Table 1: Floor space, specific annual demand and $Vh_{G/W}$ of the building types (new build)

	Floor space in m²	Specific annual demand in kWh/m²a					$Vh_{G/W}$ in (-)
		Space heating	Domestic hot water	Air conditioning	Process cooling	Electricity	
School small	5,003	68	3	21	12	12	0.11
School large	11,725	68	3	21	12	12	0.11
Consumer – NF	672	74	3	25	2	78	0.02
Consumer – EL	5,400	74	3	25	2	78	0.04
Office small	1,972	74	8	37	14	40	0.13
Office large	6,998	74	8	37	14	40	0.14
Hotel small	2,240	96	32	37	4	135	0.08
Hotel large	13,755	96	32	37	4	135	0.08
Kindergarten	559	79	3	17	0	12	0.01
Museum	16,500	74	5	29	0	37	0.02
Theater	6,700	85	6	12	0	69	0.02
Restaurant	2,500	85	50	17	0	128	0.06
GHL	24,502	96	23	33	12	115	0.31

3.4 Calculation of synthetic load profiles for non-residential buildings

The load profiles are generated with the nPro software (nPro Energy GmbH 2023) in hourly resolution by overlaying a base profile with a daily profile. The base profile can be a constant value or a seasonal course. For space heating and air conditioning, it depends on the temperature of the ambient air. The degree day method (Association of German Engineers 2013; WANG and LI 2020; Sha *et al.* 2019) is used to consider the relevant difference between room and outdoor air. It is assuming that the space heating demand increases linearly with the temperature difference between the outdoor temperature and the indoor set temperature (Verbai *et al.* 2014). The heating limit temperature, the temperature above which the building is heated, is calculated within the model depending on the insulation standard and building type-specific internal and solar gains. Analogously, the load requirement for air conditioning is calculated using the degree day method and the cooling limit temperature. The daily profiles are divided into a working day, i.e., Monday to Friday, Saturday and Sunday. Public holidays, school vacations or the time changeover are also considered depending on the location. The provided profiles and the values for the area-specific annual demand of the different building types are based on several studies, empirical values from engineering offices and monitoring reports. The resulting load profiles

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have been validated for various building types against real measurement data (nPro Energy GmbH 2023; Wirtz 2023). The values of the investigated model buildings are summarized in Table 1. The simultaneous energy Q_G, corresponds to the integral of the power of heat and cold occurring at the same time. The ratio $Vh_{G/W}$ corresponds to the relation between the simultaneous amount and the total heat demand Q_W:

$$Vh_{G/W} = \frac{Q_G}{Q_W} \tag{2}$$

3.5 Preliminary simulation for selecting the cases to be examined

To identify potentially appropriate building types depending on the prevailing boundary conditions and the system configuration, a simplified preliminary simulation is carried out in nPro (nPro Energy GmbH 2023). The calculation and optimization of the system design and operating simulation is carried out using established linear optimization methods, which are described in detail in (Wirtz *et al.* 2021). The annuity according to VDI 2067 (Association of German Engineers 2012) is used as the objective function for the optimization algorithm. Different price change factors are considered by applying them to the base prices of the costs in advance. Furthermore, climate impact costs as CO_2 costs were considered. The investment costs of the plants are applied iteratively during plant dimensioning.

The simplified system simulation is based on energy balances of all energy forms in hourly resolution with constant efficiency rates. Therefore, the performance tends to be overestimated compared to the detailed time-variable system analysis in MATLAB Simulink (The MathWorks Inc. 2020a, 2020b), in which mutual interactions between the components are also considered. The geothermal model of nPro (nPro Energy GmbH 2023) serves as a simplified representation of the ICES. It is based on an energy balance of the power extracted by a heat pump to the regeneration power supplied by cooling consumers. As the same functional principle occurs as for an ice storage tank, according to the manufacturer, it can also be used here.

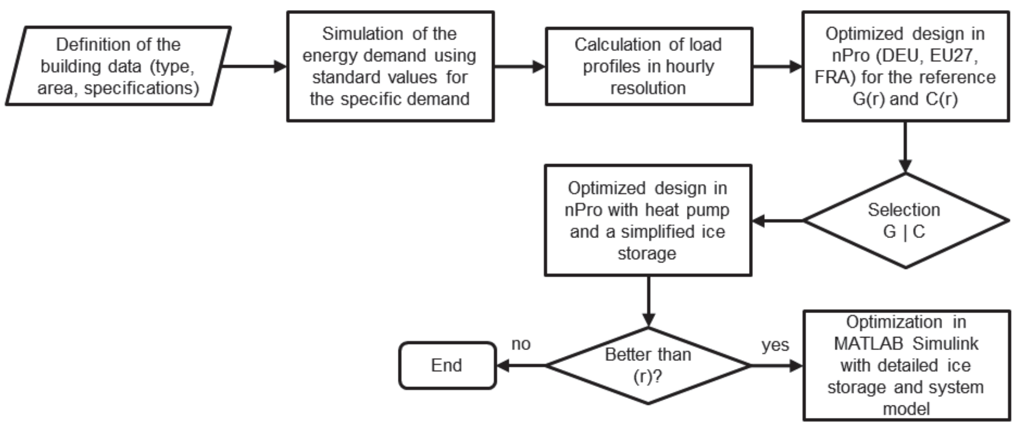

Figure 2: Process diagram of the procedure for selecting the variants for optimized storage dimensioning

The procedure for pre-selection for the computationally complex optimization calculations is displayed schematically in Figure 2. First, the respective building is defined according to Table 1. The annual energy demand and the hourly load profiles are calculated using the predefined default values. Two reference simulations are carried out without ICES, whereby an optimum dimensioning is identified for each of the three boundary conditions DEU, EU27 and FRA. In each case, it is checked whether the G(r) or C(r) variant is preferable. An iterative, optimized design with ICES is then only carried out for this optimum. The dimensioning of the remaining systems in the reference simulation is not changed due to redundancy and security of supply. The results of the optimized ICES design are compared to the respective reference. Should the integration lead to an improvement compared to the reference, a computationally intensive optimization calculation of the storage dimensioning is carried out for this building under the prevailing boundary conditions in Section 3.3. If the reference case performs better than the configuration with ICES, the case is discarded and not considered in detail, saving unnecessary computing time and capacity.

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4 RESULTS

4.1 Comparison of the developed synthetic load profiles using real measurement data

First, the real consumption data of the new hospital building in Lichtenfels (Landkreis Lichtenfels im Rahmen einer Kooperation der Technologie Allianz Oberfranken (TAO) 2022) is compared with values determined numerically using the commercial software nPro (nPro Energy GmbH 2023). The period from 1st October 2020 to 30th September 2021 is used. The data from the clinic is only used for comparison purposes and to verify the methodology. The following variational calculations for other model buildings are based entirely on synthetic load profiles.

A comparison of the required heat power shows that the curve can be reproduced well. A coefficient of determination $R^2 = 0.94$ results over the entire observation period. In an annual balance, the real total heat demand of 3050 MWh stands in contrast to a numerically determined demand of 2916 MWh, which corresponds to a difference of only 4.4 %. The yearly curve of the cooling demand, on the other hand, is characterized by a coefficient of determination $R^2 = 0.51$. The actual cooling requirement of 1146 MWh is compared to a calculated value of 1103 MWh, which is thus only 3.8 % lower. A comparison of the ordered duration curves of the heating and cooling demand is shown in Figure 3 left for further analysis. On the heating side, a value of $R^2 = 0.96$ is obtained, while on the cooling side, a value of $R^2 = 0.78$ is achieved. For a further analysis of the consumption data, Figure 3 shows on the right side both data sets averaged hourly for an exemplary transition week. The transition week shows the highest degree of agreement for both heating and cooling. Although the real values have a higher fluctuation rate, the maximum and minimum values as well as the daily time course are quite similar.

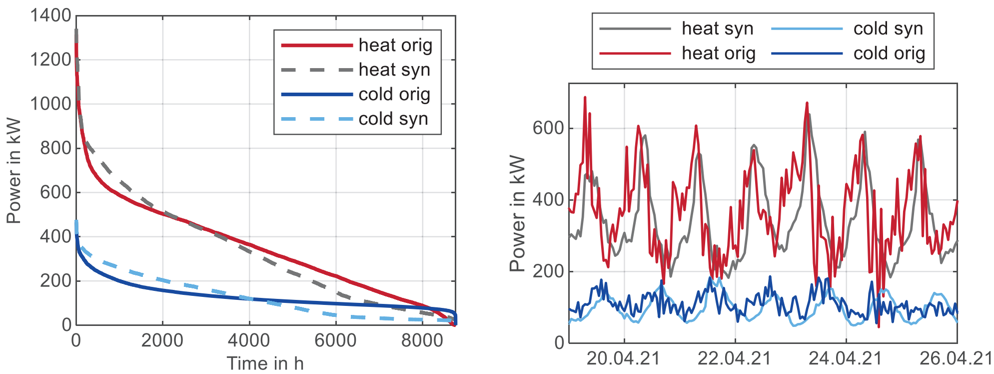

Figure 3: Measured (orig) and calculated (syn) load duration curve according to nPro for the heating and cooling demand of the GHL (1st October 2020 – 30th September 2021) (left) and hourly average heating and cooling demand for a transition week (19th April 2021 – 25th April 2021) (right)

4.2 Verification of the suitability of load profiles for storage optimization

The suitability of the synthetic load profiles compared to real consumption data is verified and the methodology thus verified. Six variants are examined, whereby a detailed optimization calculation is carried out for each with synthetic data and one with real data from the GHL. Three HP sizes are considered in each case with and without CHP. Subsequently, the detailed optimization in MATLAB is compared with a simplified simulation in nPro (nPro Energy GmbH 2023).

Using the smallest examined HP in the S cases, the volumes differ noticeably by ca. 37 % and thus also the determined pipe lengths. With a medium and large HP size, however, the results are almost identical with a difference of 0.3 and 0.9 %. In all C cases, the algorithm converges to the lower limit of the variation range, regardless of the HP size. Under the given boundary conditions, this is mainly due to the fact that a larger dimensioning increases the running time of the heat pump, which in turn reduces the operating time of the CHP.

The possible proportions for heating and cooling provision and the contribution of the ICES to the sum of heating and cooling of the optimized variants are largely comparable. Using the real data in the cases without CHP, an approx. 29 to 40 % larger share of cooling can be achieved. The share of the predominant heat supply is significantly more similar to these cases with a maximum deviation of 2 to 12 %. As a result, the share of total generation is nearly equal, with a deviation of

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approx. 15 to 17 % for both data sets. In all C-cases, all proportions are almost negligibly low and identical. In addition, the resulting CO_2 emissions of the variants under consideration and a reference simulation without ICES with and without CHP are compared. The progression and thus the order of the variants is identical for both data sets.
For the economic evaluation of the different cases, the annuities are compared in sum with the different climate impact cost rates for all cases. The sequence from optimum to pessimum is identical for all variants with both data sets. Thereby, it can be seen that the optimization with real data is similar to the one with the numerically determined synthetic data sets, whereby these can be used well for an estimation of the system configuration and storage dimensioning. In contrast to the simplified simulation, the dynamic system behavior, real control mechanisms, mutual interactions and the detailed behavior of the storage system are considered in the computationally intensive system simulation. Therefore, in a further step, the dimensioning and the resulting results of the system operation of nPro are compared with the detailed simulations in MATLAB Simulink. A comparison of the calculated storage sizes indicates that the simplified calculation tends to identify a configuration in a similar direction in the G-cases. In both optimization calculations, the lower limit of the variation range for the storage volume is selected in all C-cases.
The share of the ICES in the provision of heating and cooling for both simulation variants is generally overestimated with the simplified simulation. One of the reasons for this is the fact that mechanisms such as storage losses and mutual interactions between the systems are not considered in detail. The crucial difference, on the other hand, is that in nPro a stepless output control of the HP is considered, which considerably extends its runtime and operating times. In the C-cases, all proportions are almost identical and at the same time negligible in both simulation approaches due to the small storage size. As a result, it can be seen that the simplified simulation can be used to filter out these variants. In terms of the resulting annual CO_2 emissions, the values calculated in detail are largely higher for all variants, as losses, operating restrictions and partial load efficiencies are also considered. Finally, the resulting costs in terms of annuity and climate impact costs are compared. With both simulation approaches, the order in the S cases is rather similar. Regardless of the level of detail of the simulation, the results for all C cases with ICES are quite similar, whereby the costs increase with the size of the heat pump.
Concluding, there is a tendency to overestimate the share of the ICES in the to the simplified simulation, mainly as a result of neglecting complex control mechanisms. This means that the absolute values of generation and the resulting costs and CO_2 emissions can also differ. However, the identification and classification of the variants are consistent. Therefore, the simplified and time-saving simulation is well suited for rough estimation and selection, while the detailed system simulation considers all phenomena of real plant operation.

4.3 Selection of the buildings

To cover a broad range of non-residential buildings under different boundary conditions, a systematic analysis of the twelve model buildings from eight categories of section 3.4 is carried out. For this purpose, for each of the considered buildings, the economic and ecological boundary conditions of DEU, EU27 and FRA are utilized. An extensive analysis like the detailed variation computations of the verification in the previous section would not be feasible at this point, as this would lead to unacceptable calculation times. The resulting 216 computationally intensive optimizations in addition to 72 reference simulations would lead to a pure computing time of 48 months using a parallelization on 44 threads. The effort for model creation and evaluation must also be added. However, this would involve unnecessary variants in which the integration of a CHP or ICES would not be profitable and the optimization algorithm would converge towards the specified minimum.
Therefore, the described methodology of Section 3.5 is applied in the following to identify suitable configurations employing preliminary simulations. The simplified simulation in nPro (nPro Energy GmbH 2023) is used to conduct an optimized sizing for the GB, the CHP and the CC for each of the 108 resulting cases. In G(r), the design of the GB is identical for the respective building, regardless of the location, since the reliability of supply must be guaranteed via the single heat generator. In the cases C(r) and ICES, on the other hand, different dimensions can be identified depending on the CHP size. Due to the redundancy requirement described in (Griesbach *et al.* 2023b), no reduction of the GB size compared to G(r) occurs for ICES. Except for the "Hotel large" building under the constraint of EU27, the minimum CHP size is selected in all EU27 and FRA cases, as the CHP is not competitive against

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the GB. Consequently, in the ICES instance, mostly no CHP is identified. In cases with CHP, its size corresponds to that of variant C(r) for redundancy reasons, see (Griesbach *et al.* 2023b). Due to the same redundancy requirements, the size of the CC does not differ within the configurations and the boundary conditions, while the CC is the single cold generator in the cases G(r) and C(r). Under the frameworks of DEU, the configuration with CHP is identified in nine cases and in three cases without CHP. For EU27, the configuration with CHP is only selected for one building and for none under FRA boundary conditions. In the ICES design, an extraction power of 20 kW is specified as the lower limit for the iterative optimization of the dimensioning. Under DEU boundary conditions, this minimum value is identified in all cases. For EU27, this limit value is identified in seven out of twelve buildings and for FRA in 50 % of the examined buildings.

Table 2: Results of the annuity including climate impact costs of the preliminary simulation in nPro for selecting the variants

	Annuity in sum with climate impact costs 0P in €/a								
	DEU			**EU27**			**FRA**		
	G(r)	**C(r)**	**ICES**	**G(r)**	**C(r)**	**ICES**	**G(r)**	**C(r)**	**ICES**
School small (1)	152,313	150,478	154,019	148,470	158,905	**136,778**	142,874	158,905	**112,279**
School large (2)	342,975	278,818	291,127	333,307	354,257	**273,378**	321,363	348,625	**224,685**
Consumer – NF	26,359	28,409	36,041	26,005	33,689	33,637	25,534	36,082	30,785
Consumer – EL (3)	151,101	128,503	139,271	148,642	161,417	**143,002**	144,444	163,773	**122,304**
Office small (4)	76,168	77,689	79,029	73,334	85,080	**71,375**	69,665	86,234	**62,269**
Office large (5)	241,830	214,073	222,993	232,142	242,243	**205,395**	218,948	235,488	**164,260**
Hotel small (6)	101,428	88,294	96,842	100,160	109,642	**95,411**	97,285	113,704	**86,858**
Hotel large (7)	551,190	341,392	354,532	541,676	523,052	**440,129**	527,267	543,824	**330,068**
Kindergarten	24,916	34,410	37,149	24,900	39,083	36,011	24,719	41,072	34,538
Museum (8)	437,216	288,773	301,284	427,657	436,280	350,530	414,166	430,768	**276,614**
Theater (9)	177,713	123,634	135,311	178,935	188,296	179,822	179,154	195,728	**176,093**
Restaurant	105,387	84,621	93,829	106,537	115,312	112,337	106,829	123,314	110,078

The resulting annuities in sum with climate impact costs of the preliminary simulations are listed in Table 2. The combinations in which the ICES setup represents an improvement to the reference are highlighted in bold. These are examined within the computationally intensive variation calculations in the next chapter. For the detailed plant simulations in the following chapter, real available plants are used. In nPro (nPro Energy GmbH 2023), however, the plant size is continuously adjusted, resulting in slight differences in the dimensioning of the plants. The detailed analysis in MATLAB is always performed using the available plant from the same series as the validated models from (Griesbach *et al.* 2023b). In each case, the unit that matches the values from nPro as closely as possible is used.

4.4 Results of the detailed simulation

Through the optimization algorithm and the procedure described in section 3.5, the optimum storage dimensioning is identified for each configuration previously selected. In twelve cases, the algorithm converges against the specified lower limit of the volume of 20 m³. However, within the four configurations "School small", "School large", "Office large" and "Hotel large", a volume is identified within the defined optimizing interval that tends to be larger under the FRA than with EU27.

In Figure 4, the proportion of the overall supply that can be achieved by the producers with the respective storage volume is shown with the numbering according to Table 2, where (-E) stands for EU27 and (-F) for FRA. Moreover, the ratios for the respective reference case without ICES are included. In the cases with minimal storage volume, which represents a hardly usable capacity, the contribution of the HP is quite small. In addition, the HP must frequently be blocked due to low inlet temperatures, see (Griesbach *et al.* 2023b). The highest proportion of 53 % can be achieved under the boundary condition of FRA in case 2-F, while the lowest proportion of 15 % can be provided in case 2-E with the significantly smaller system in EU27. Comparable trends can be seen in 5-E with an HP ratio of 18 % and in 5-F with 43 %. Whereas in 1-F the algorithm approaches a hardly usable minimum, in 1-E the HP can cover 20 % of the demand with a relatively small storage volume. Using the largest identified storage volume, in 7-F the HP can achieve a proportion of 37 %. In 7-E, the contribution of the ICES is minimized by the minimum storage volume, while the CHP runtime is maximized. Except for case 7-E, heat is supplied entirely by the GB in all reference simulations. Correspondingly, the lower

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part of the figure shows the proportion of the ICES in the provision of cooling, although the amounts in variants with minimal volumes are also quite small. In these cases, the regeneration and the cold water network as a direct source for the HP can hardly be used. The largest possible proportion of the cooling supply of 27 % from the ICES can be achieved in case 1-E. Contrary to the heat supply, the proportion of the cooling supply in the cases 2 and 5 can hardly be improved by increasing the storage volume. Thus, in 2-E it accounts for 19 %, and in 2-F for 22 %, while in 5-E it is 17 % compared to 18 % in 5-F. The main reason here is the time lag between the heating and cooling demand. As a consequence, the cooled storage tank is warmed by the surrounding ground and can therefore contribute less to the provision of cooling. This effect is maximized in 7-F, in which the cooling demand is primarily caused by air conditioning, see Table 1. The amount of process cooling is negligible, which means that losses to the surrounding ground are high due to the long time offset. In addition, the reference cases include the option of FC, whereas it is not used in the configurations with ICES. The majority of cooling is provided by the electrically operated CC in all combinations.

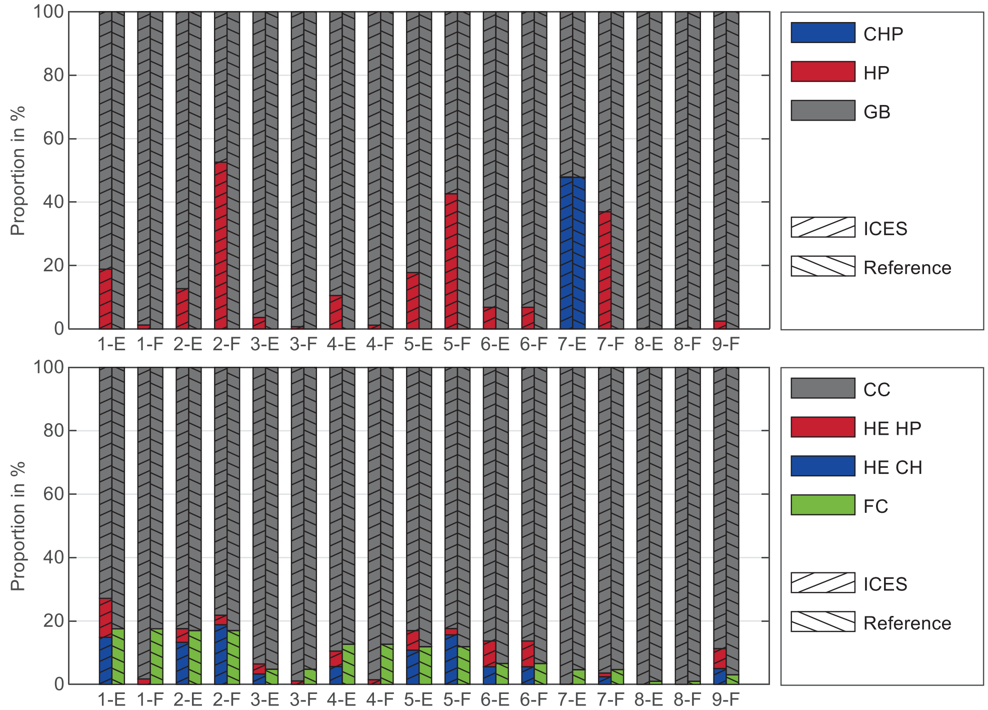

Figure 4: Composition of the heat (up) and cold (bottom) generation of the composite system with ICES and the reference simulation

The resulting annual CO_2 emissions are illustrated in Figure 5. The values of the reference simulations and the ICES cases using the minimum storage size are almost identical, as the ICES can only contribute to a very limited amount. Compared to the reference, a reduction of 55 % can be achieved in 2-F. The high proportion of the HP in the heat supply is the main reason for this. In case 2-E, in which the share of cooling supply is almost identical, the improvement in terms of CO_2 emissions amounts to only 18 %, as the contribution of the HP is significantly lower. A similar trend can be seen with 5-F, where the reduction is 49 % due to the high proportion of HP, while in 5-E the improvement is only around 20 % due to the lower proportion of HP while providing a similar amount of cooling. A similar behavior can be observed with 7-F, where the noticeable proportion of the HP reduces CO_2 emissions by 40 %, whereby the contribution to the provision of cooling is very low. The lowest improvement of 15 % compared to the reference can be observed in case 1-E, although the largest possible proportion of cooling is provided. Overall, this shows a predominant influence of heat on CO_2 emissions, while the influence of cooling plays a subordinate role under the given boundary conditions.

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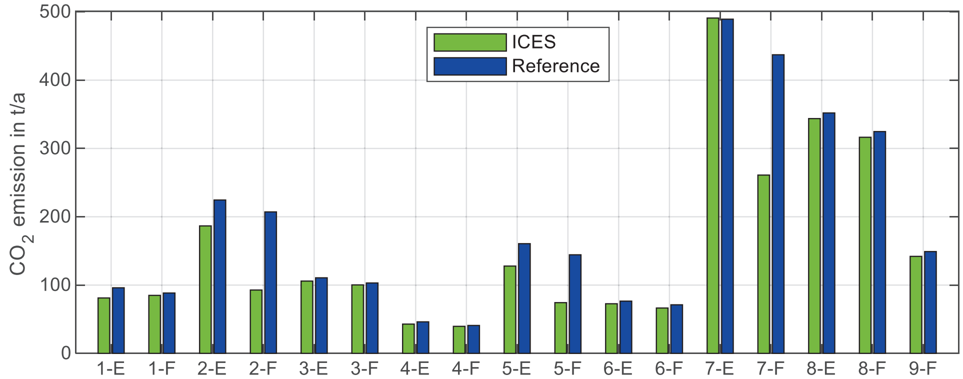

Figure 5: CO_2 emissions of all configurations selected previously in nPro for optimization with ICES and the reference simulation in MATLAB Simulink

The resulting annuity in combination with climate impact costs according to Section 3.2 using different $PTPR$ is shown in Figure 6. The direct costs consistently increase as a result of the ICES integration. Based on these constraints, the additional investment cannot be compensated by savings in demand-related costs. Even with a multi-criteria assessment using $PTPR = 1$ %, the reference performs more favorably in all combinations. However, with $PTPR = 0$ %, the combined evaluation with ICES can be beneficial. Here, an improvement of 0.1 % can be achieved in the case 5-E, 6.2 % in the case 2-F and 8.5 % in the case 7-F. Despite noticeable reductions in CO_2 emissions, higher costs must be accepted in the other cases, regardless of the usable storage capacity.

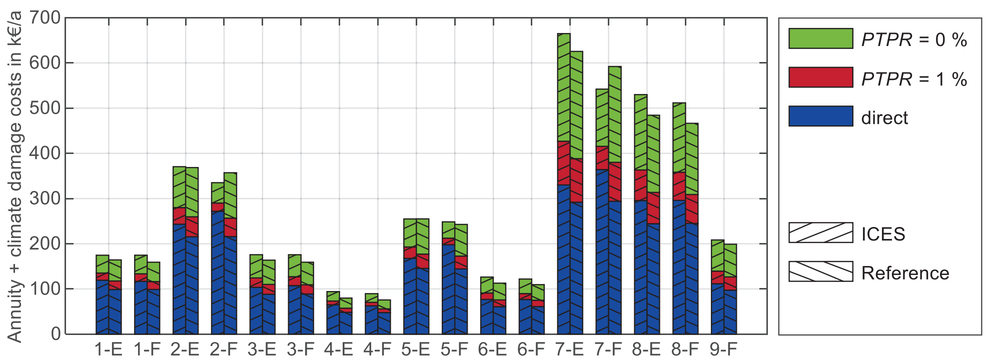

Figure 6: Annuity and climate impact costs with different $PTPR$ of all pre-selected configurations for optimization with ICES and the reference simulation in MATLAB Simulink

In conclusion, in Figure 7 the considered buildings are shown as a function of the annual heating and cooling demand and $Vh_{G/W}$ according to Table 1. According to the detailed variational calculations, the implementation of an ICES can be recommended in the "School small", "School large", "Office large" and "Hotel large" buildings. These buildings have the following features in common, which can therefore be regarded as minimum requirements for an ICES integration. The heat requirement should be at least around 355 MWh per year. This minimum demand is required to ensure that savings from reduced gas consumption and climate impact costs compensate the higher investment. In the same context, the annual cooling demand should be at least about 165 MWh. At lower heating or cooling requirements, the combined evaluation parameter becomes less favorable than the reference, which is characterized in particular by low investment costs in the absence of ICES. A further similarity of the identified configurations is the fact that $Vh_{G/W}$ must be at least approx. 8 %. Generally, higher values are beneficial for the performance and efficiency of the system. On the one hand, the cooling network can be used more frequently as a direct energy source for the HP via HE HP, which increases the inlet temperatures of the brine side and thus the efficiency of the HP. Furthermore, the time lag between heating and cooling demand reduces the required storage capacity, resulting in lower investment costs.

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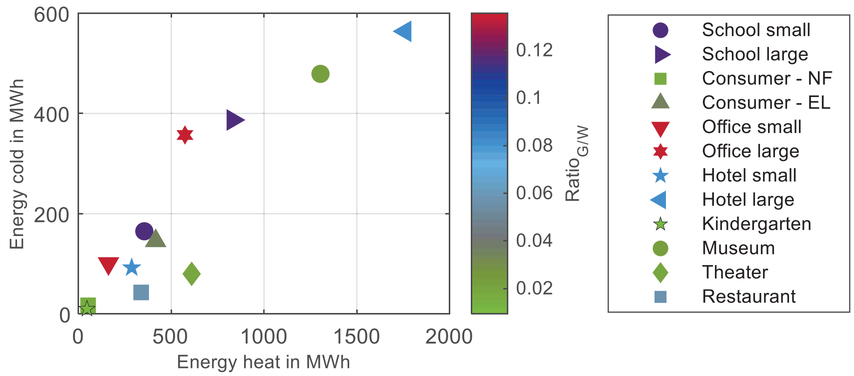

Figure 7: Annual energy demand for heating and cooling supply as a function of $Vh_{G/W}$

5 CONCLUSION

In order to counteract the advancing climate change and rising energy prices, the search for more efficient solutions for the provision of heating and cooling in buildings is becoming increasingly important. Hence, in this work, a systematic method for the evaluation and optimization of integrated systems with ice energy storage in various non-residential buildings using boundary conditions for environmental and economic parameters for different locations is developed.

To identify potentially suitable building types and plant configurations under prevailing boundary conditions, first systematically simplified preliminary simulations were performed. Detailed optimization calculations were then started only for these preselected cases. Thereby, the calculation time is reduced from about 48 months to below 4 months. The integration of an ICES requires a relatively high heating and cooling demand, so savings in demand-related costs compensate for the additional investment. Additionally, simultaneous heating and cooling is often necessary, which allows the cooling network to serve as a direct energy source for the HP as well as to regenerate the storage tank frequently. Typically, air conditioning alone does not meet the required level of simultaneity, so a form of process cooling is required. Among the model buildings studied, a small and a large school, a large office building, and a large hotel fulfill these constraints.

The proposed methodology can be extended to other building classes with high heating and cooling requirements, such as data centers, or to districts consisting of different building types. Additionally, the model can be enhanced to include other system components like solar thermal, actively cooled PV modules, and solar air absorbers.

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Declaration of Competing Interest

The authors declare that there is no conflict of interest.

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