Modelling and Implementation of Ice Storage Systems: Use Cases and Performance evaluation

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Abstract

This study investigates the performance of ice storage systems integrated with heat pumps and solar collectors in various configurations. Using a validated mathematical model of the ECOTHERM Ice Memory System, simulations are conducted in MATLAB/Simulink with the Carnot Toolbox. Several case studies are defined by varying the housing types and system components. This works goal is to evaluate system efficiency through metrics such as the Seasonal Performance Factor (SPF) and the Seasonal Coefficient of Performance ($SCOP_{HP}$). The results show that the energy efficiency of the building significantly influences the required ice storage volume and overall system performance. In highly efficient buildings, smaller ice storage volumes are sufficient, while buildings with higher heating demands require substantially larger storage capacities. The study also highlights the importance of balancing collector area and storage volume to optimize regeneration and maintain a minimum state of charge (SOC). These findings provide valuable insights into the design and implementation of efficient, solar-assisted ice storage systems in residential applications. Future work includes sensitivity analysis to assess economic and ecological impacts of the predefined case studies.

Keywords: case studies, ice storage, mathematical modelling, seasonal performance factors, simulation

1. Introduction

Ice storage systems play a crucial role in the field of heating and cooling due to their excellent ability to efficiently store thermal energy for later use. This capability significantly reduces the reliance on conventional energy sources during peak demand periods, thereby enhancing energy efficiency and sustainability. When integrated with heat pumps and solar collectors, ice storage systems offer a substantial advantage over traditional heating and cooling methods. This synergy not only optimizes energy usage but also contributes to a more resilient and environmentally friendly energy infrastructure. The importance of ice storage systems lies in their potential to transform how we manage thermal energy, making them an indispensable component in the pursuit of sustainable energy solutions.(Carbonell et al., 2014)

Beyond their technical sophistication, ice storage systems are increasingly recognized for their strategic role in balancing heating and cooling demands within buildings. By leveraging the latent heat of fusion during phase change processes, these systems can store large amounts of thermal energy in compact volumes, making them ideal for space-constrained urban environments (Chebli and Mechighel, 2025). During periods of low energy demand or surplus renewable energy generation, ice can be produced and stored, then later utilized to meet peak cooling or heating needs without drawing heavily on the grid. This load-shifting capability not only reduces operational costs but also enhances grid stability and supports the integration of intermittent renewable sources (Sun et al., 2024). In buildings with fluctuating thermal loads—such as offices, hospitals, or residential complexes—ice storage systems provide a flexible and reliable solution to maintain indoor comfort while minimizing environmental impact (Fan and Luo, 2018).

Understanding and optimizing ice storage systems relies heavily on mathematical modelling, which provides crucial insights into their thermodynamic behavior, performance, and efficiency. These models utilize equations from heat transfer, fluid dynamics, and thermodynamics to simulate the intricate interactions within the system. A key component of this modelling is predicting the thermal behavior of ice storage mediums, such as water or phase change materials, during charging and discharging cycles (Buchner, 2005; Guittet et al., 2025; Zhao et al., 2024).

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This involves analyzing heat transfer mechanisms, phase change phenomena, and energy storage capacity under different operating conditions. Simulating various use scenarios is particularly important, as it allows researchers to evaluate how the system performs under diverse conditions, identify potential issues, and optimize the design for real-world applications. By exploring different scenarios, simulations ensure that ice storage systems are robust, efficient, and adaptable to varying demands.

Recent advancements in the mathematical modelling of ice storage systems have expanded the scope and precision of simulation tools used in energy applications. Vivian et al. (2023) proposed a quadratically-constrained mixed-integer programming (MIQCP) formulation to optimize the sizing and operation of seasonal ice thermal storage systems. Their model effectively captured both latent and sensible heat behaviors, demonstrating the importance of integrating detailed thermodynamic principles into system design (Vivian et al., 2023). In the context of machine learning, (Wenbo et al., 2024) introduced an XGBoost-based predictive control model for ice storage cooling systems in high-rise buildings, achieving a 41.9% reduction in electricity costs through dynamic load forecasting and control optimization. Additionally, (Bailey, 2010) developed a one-dimensional analytical model for phase change material (PCM) thermal storage systems, validated through CFD simulations and experimental data, offering a foundational approach for sizing and performance analysis of PCM-based ice storage units.

In a reference work (Daborer-Prado and Wagner, 2024), the mathematical model of an innovative ice storage system was developed to represent the ECOTHERM Ice Memory System. In this system, 12 spiral flat coil cooling bundles were connected in parallel. The developed ice storage model was then integrated into a comprehensive system containing a single-family house, a heat pump and a solar thermal collector field. The state of charge (SOC) of the ice storage was calculated as well as the Seasonal Coefficient of Performance ($SCOP_{HP}$) of the heat pump and the Seasonal Performance Factor (SPF) of the whole system. The previously mentioned studies collectively emphasize the growing sophistication and interdisciplinary nature of ice storage modelling, integrating thermodynamics, optimization, and data-driven techniques to enhance system performance and sustainability.

In the scope of this study, in order to evaluate the performance of the ice storage system in various configurations, the mathematical model from the reference study (Daborer-Prado and Wagner, 2024) was integrated into a comprehensive system that includes a diverse range of components. This integration allowed for a detailed analysis of how the ice storage system interacts with different elements within the overall system. The results from these simulations were then compared in order to identify the most optimal configuration for using the ice storage systems. This comparison aims to pinpoint the configuration that maximizes efficiency, performance, and reliability, ensuring the best possible utilization of the ice storage systems in practical applications.

2. Methods and methodology

In this work several case studies were defined and then simulated in order to analyze the performance of an ice storage system. The simulations were performed in MATLAB/Simulink (MATLAB/Simulink 2024) using the Carnot Toolbox (CARNOT Toolbox 2024). Figure 1 depicts the basis system analyzed in the reference study (Daborer-Prado and Wagner, 2024). All components outlined with dashed blue lines were modified in the simulations conducted in this work to align with the predefined use cases. In order, these components correspond to:

- 1: Different ice storage sizes
- 2: Different sizes of unglazed collectors
- 3: Type of house used in the system

The system comprises a single-family house, an ice storage unit, a heat pump, and a solar thermal collector field. The heat pump supplies the thermal energy needed to meet the house's heating demand. To operate, the heat pump draws thermal energy from the ice storage, causing the water within it to cool and eventually freeze due to the heat extraction. As a result, the ice storage requires periodic regeneration.

This regeneration is powered by the solar thermal collector field. The process is regulated based on the temperature difference between the collector outlet and the medium inside the ice storage. When this temperature difference exceeds 5 K, the solar pump is activated to initiate regeneration. Conversely, if the temperature difference drops below 1 K, the solar pump is turned off.

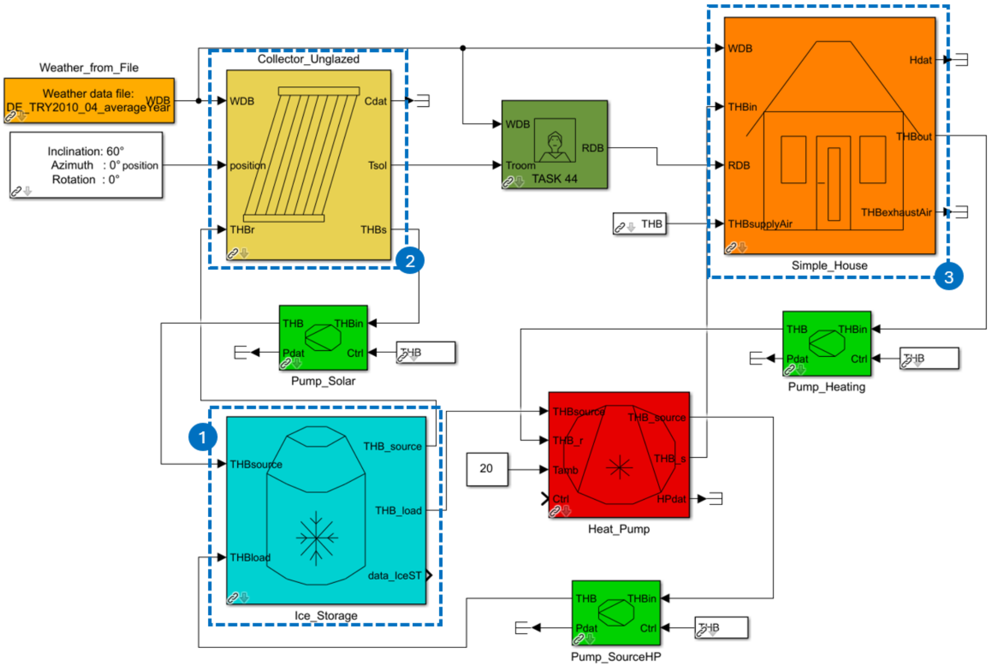

Figure 1: Simulink view of the ice storage integrated into a comprehensive system

All the different scenarios were then compared by the calculation of the Seasonal Performance Factor. The SPF measures the efficiency of a heating or cooling system over an entire season. It is calculated by dividing the total energy output by the total electrical input, providing a comprehensive view of the system's performance under varying seasonal conditions as presented in (Eq. 1) (Malenkovic et al., 2013).

$$SPF = \frac{\int \left(\dot{Q}_H + \dot{Q}_{DHW} + \dot{Q}_C\right) dt}{\int \sum P_{el}\, dt} \qquad \text{(Eq. 1)}$$

Where the SPF (-) is the seasonal performance factor, $\dot{Q}_H$ (kW), $\dot{Q}_{DHW}$ (kW) $\dot{Q}_C$ (kW) are the thermal powers for heating, domestic hot water and cooling, respectively, and finally $\sum P_{el}$ (kW) describes the overall electrical power consumption of all components.

Another factor taken into consideration when analyzing the differences between the use cases was the Seasonal Coefficient of Performance. It measures the energy efficiency of a heat pump over an entire heating season. Unlike the standard Coefficient of Performance (COP), which provides a snapshot of efficiency at a specific moment, $SCOP_{HP}$ considers the varying outdoor temperatures and operating conditions throughout the season. This metric offers a more accurate representation of the heat pump's overall performance and energy savings potential and can be calculated as follows in (Eq. 2):

$$SCOP_{HP} = \frac{Q_{H,HP}}{W_{el,HP}} \qquad \text{(Eq. 2)}$$

Where the $SCOP_{HP}$ is the seasonal coefficient of performance (-), $Q_{H,HP}$ (kWh) is the annual thermal energy which is supplied by the heat pump and finally $W_{el,HP}$ (kWh) is the annual electrical energy which is consumed by the heat pump.

3. Results and discussion

Table 1 summarizes the use cases considered in this study. The cases were designed to ensure that the simulations reflect a broad range of practical scenarios and deliver results that are both comprehensive and applicable to real-world conditions. The asterisk "*" marks the variation of the specific component is each use case.

Table 1: Use Cases considered in this work

Case	Values
Use Case A	Single family house: 15 kWh/(m²a) Ice storage: * Unglazed collector: * Location: Germany
Use Case B	Single family house: 45 kWh/(m²a) Ice storage: * Unglazed collector: * Location: Germany
Use Case C	Single family house: 100 kWh/(m²a) Ice storage: * Unglazed collector: * Location: Germany

3.1 Use Cases

As outlined in Table 1, various use cases were simulated throughout this study. In each scenario, different parameters were systematically varied to observe and assess the system's response. This section provides a detailed description of all simulated cases, along with an evaluation of the results obtained. The objective in all use cases is to ascertain the optimal size of the ice storage. To this end, the parameters of the individual components are modified and the effects on the overall system are examined. The aim is to guarantee that the building's heat demand is met and that the ice storage maintains a SOC of at least 0.2, which indicates a minimum of 20% liquid water content in the ice storage. This is to prevent the occurrence of blasting effects resulting from the thermal expansion of the ice.

- Use Case A:

In the first scenario, a single-family house with a specific heating demand of 15 kWh/(m²·a) is considered. The system is situated in Germany and reflects a year with typical climatic conditions. The house itself has a heated living area of 120 m². The regeneration of the ice-storage system is conducted though the use of unglazed solar collectors. To evaluate the impact of the unglazed solar collector area on the required ice storage size, simulations were conducted in which the collector area was systematically varied. For each configuration, the corresponding minimum ice storage volume was determined in such that the SOC of the ice storage did not fall below a threshold of 20%.

Figure 2 illustrates the simulation outcomes for use case A, highlighting the required volume range of the ice storage, which varies between 4 m³ and 6 m³ depending on the unglazed solar collector regeneration area. The results indicate a clear inverse relationship between the size of the regeneration area and the necessary ice storage volume. Specifically, an expansion of the regeneration area leads to a reduction in the required ice storage capacity. This effect can be attributed to the accelerated regeneration process, which enables continuous operation of the heat pump system with a smaller ice storage volume. The correlation between the collector area and the ice storage volume exhibits an approximately linear trend, as evidenced by a coefficient of determination of $R^2 = 0.9878$.

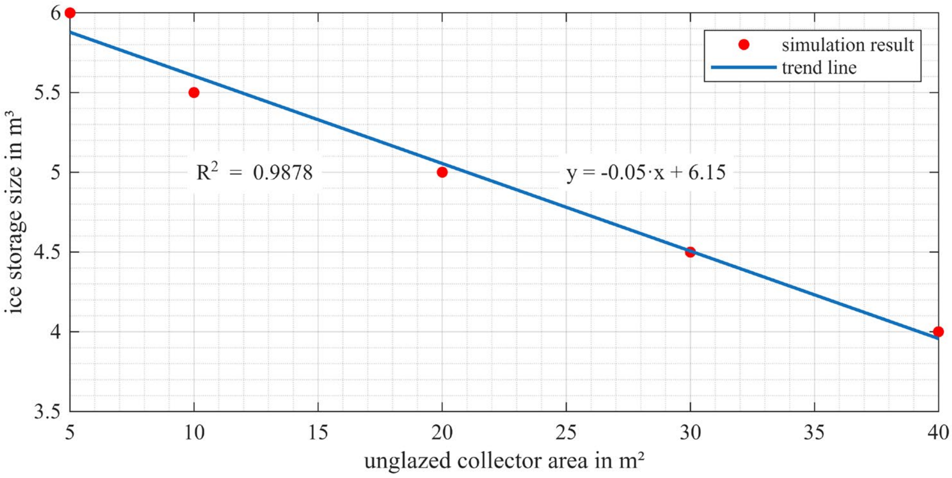

Figure 2: Dependence of the ice storage volume on the unglazed collector area in Use Case A

Figure 3 shows the SOC annual progression of the various ice storage and unglazed collector area combinations of Use Case A. It can be observed that in the individual configurations, the ice storages were dimensioned such that the SOC remains above 0.2 for the majority of systems configurations. An exception is observed in the configuration compromising a 40 m² collector area and a 4 m³ ice storage, where the SOC temporarily falls below this threshold. Due to the high energy efficiency standard of the building in Use Case A, the required ice storage volumes are comparatively low. In the configuration featuring a 30 m² solar thermal collector field and a 4.5 m³ ice storage unit, the SOC threshold of 0.2 is already exceeded, indicating that the system operates beyond the intended limit under these conditions.

The comparable ice storage volumes in Use Case A results in the annual SOC profiles showing similar characteristics. A minimum SOC of 0.2 is typically reached after approximately 300 h, followed by a recovery on nearly all systems to values exceeding 1.0, indicating that the water in the ice storage has returned fully to a liquid state. However, in the configuration with a 5 m² collector area and a 6 m³ ice storage, the SOC remains below 1 until 1700 hours, suggesting that the storage remains partially frozen in this period. During the summer months, the SOC increases in all configurations, reaching a maximum value just below 1.4, which corresponds to a water temperature of approximately 30°C. At the beginning of the heating season, the state of charge (SOC) decreases across all system configurations in Use Case A.

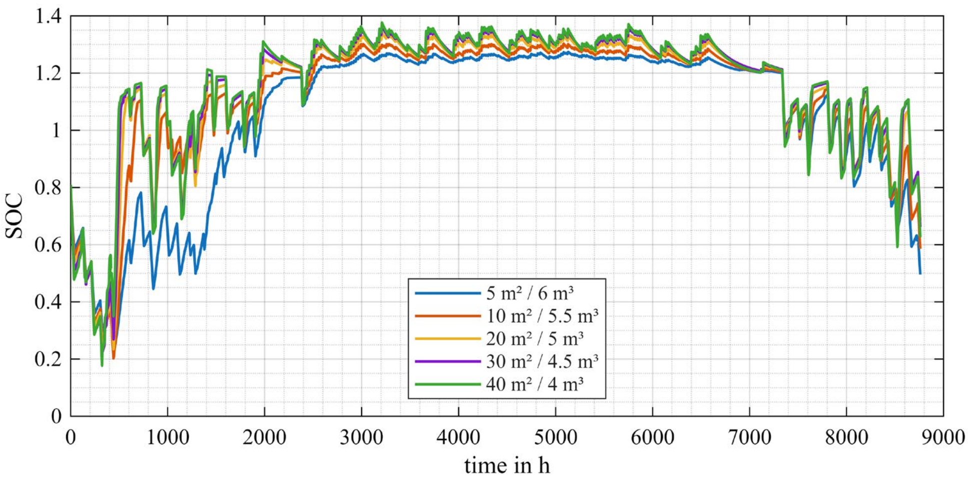

Figure 3: SOC profiles of the individual ice storge systems in Use Case A

- Use Case B:

In the second scenario, the energy efficiency standard of the single-family house is changed to 45 kWh/(m²a). The heated living space and geographical location of the building are identical to those in Use Case A. As in Use Case A, the area of the unglazed solar thermal collector is varied, and the corresponding ice storage capacity required for the heating system is analyzed. The collector area is again examined within a range of 5 m² to 40 m². The simulation results of Use Case B are shown in Figure 4. To avoid falling below an SOC 0.2, this use case requires an ice storage volume of 8.6 m³ and an unglazed solar collector area of 40 m² for regeneration up to a volume of 15 m³ with a solar collector area of 5 m². Furthermore, the curve is clearly no longer as linear as in Use Case A, as indicated by a coefficient of determination of $R^2 = 0.6910$. Comparing the required ice storage volumes for this Use Case with those for Use Case A reveals that they are now slightly more than double, even though the specific heat demand of the building in this scenario is three times higher. This indicates that the performance coefficient of the heat pump must change in each scenario, suggesting a change in system efficiency.

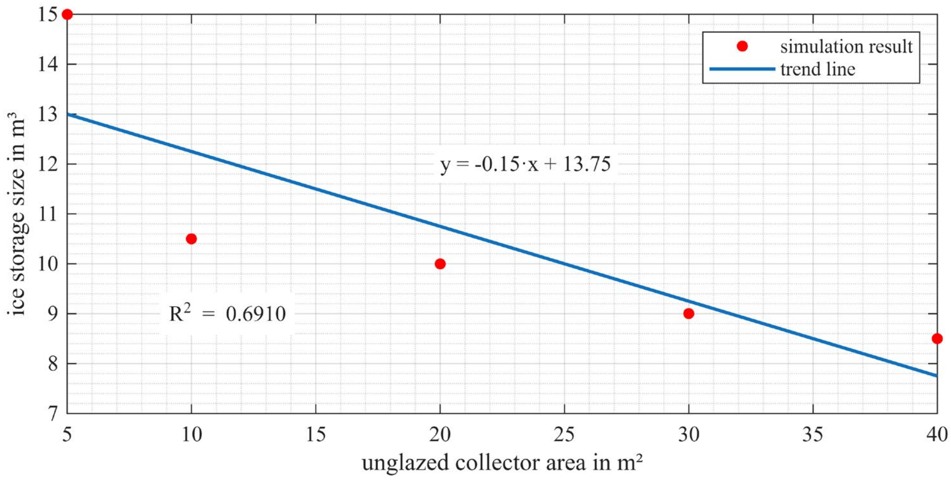

Figure 4: Dependence of the ice storage volume on the unglazed collector area in Use Case B

As illustrated in Figure 5, the SOC profiles of the individual configurations in Use Case B demonstrate a comparable trend to that observed in Use Case A. The configurations with smaller ice storages (40 m²/8.5 m³, 30 m²/9 m³, 20 m²/10 m³, 10 m²/10.5 m³) attain the lower SOC limit of 0.2 after approximately 300 hours. Conversely, the configuration with a larger ice storage volume of 15 m³ and a collector area of 5 m², attains the lower limit after approximately 1300 hours. It can be seen that, the configurations with a smaller volume of the ice storage and a bigger collector area, react more quickly during the process of discharging the ice storage and undergoing the regeneration process. The combinations with an ice storage volume smaller than 10 m³ reach an SOC above 1 for the first time after approximately 600 hours. The combinations with a larger ice storage volume than 10 m³ reach this value after 2000 hours and 2600 hours, respectively. During the summer months, all configurations exhibit a relatively similar behavior, with an SOC ranging from 1.2 to 1.3, until a decline is observed at the beginning of the heating season.

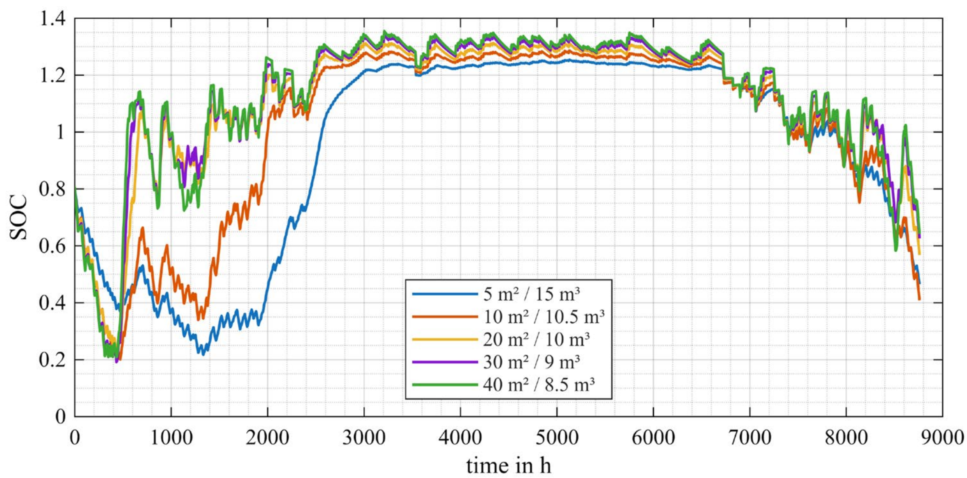

Figure 5: SOC profiles of the individual ice storge systems in Use Case B

- Use Case C:

In the last Use Case, the specific heating demand of the single-family house is increased to 100 kWh/(m²a), thus describing a building with a poor energy standard. As with the preceding Use Cases, the unglazed collector area for the regeneration of the ice storage varies between 5 m² and 40 m² and the necessary size of the ice storage to meet the building's heating demand and maintain a SOC of 0.2 is examined. As illustrated in Figure 6, the simulation results for Use Case C demonstrate that the required ice storage size ranges from 15.5 m³ with an unglazed solar collector area of 40 m² to a volume of 37 m³ for a collector area of 5 m². Therefore, the necessary ice storages volumes are significantly higher in this Use Case than in previous ones. As illustrated in Figure 6, a collector area exceeding 20 m² has a negligible effect on ice storage size, while the necessary ice storage volume experiences a substantial increase with smaller collector area. In contrast to Use Case B, this Use Case shows a better linear correlation, as indicated by an R^2 value of 0.7474.

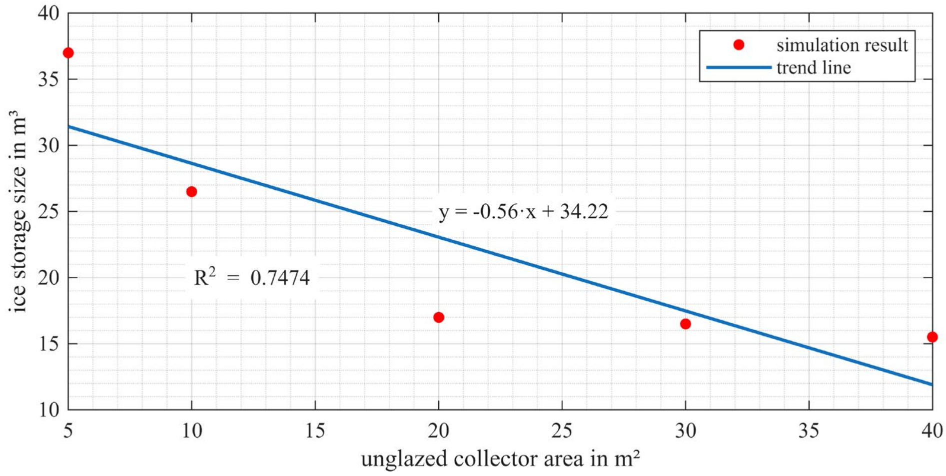

Figure 6: Dependence of the ice storage volume on the unglazed collector area in Use Case C

As shown in Figure 7, the SOC profiles for the individual configurations in Use Case C demonstrate a similar trend to that observed in Use Case B. Specifically, the figure indicates that systems with a smaller ice storage volume are the first to reach the lower SOC limit of 0.2. This event typically occurs at approximately 400 hours. For systems with a larger volume, this occurrence is observed at approximately 1400 hours (10 m²/26.5 m³) and 1900 hours (5 m²/37 m³). However, even in this Use Case, systems with a small volume reach a SOC above 1 more quickly. The system with the largest ice storage volume, for example, only reaches an SOC larger than 1 after 3500 hours. This indicates that after 3500 hours there is no more ice in the storage and all the water inside is in liquid form. During the summer months, the individual configurations converge one more and after approximately 7400 hours, the SOC falls below 1 for the first time during the heating period.

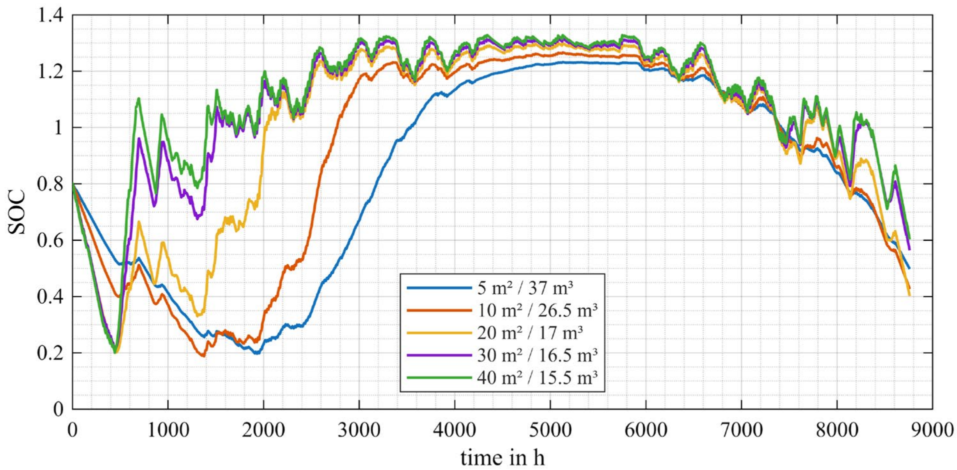

Figure 7: SOC profiles of the individual ice storge systems in Use Case C

3.2 System efficiency:

A critical component of heat pump systems pertains to their efficiency. In this study, efficiency is described using both the SCOP, see equation 2, and the SPF, see equation 1. The values were calculated for each of the three Use Cases. Figure 8 shows the results of the simulations regarding the efficiency of the individual heating systems. The red markers describe the system efficiency of Use Case A, with a specific heating demand of the single-family house of 15 kWh/(m²a); the blue markers describe the efficiency of Use Case B, with a specific heating demand of 45 kWh/(m²a); and finally, the magenta markers show the results of Use Case C, with a specific heating demand of 100 kWh/(m²a). The SCOP only considers the heat pump itself, while the SPF considers heat pump and all the electrical energy required for operation. In addition to the heat pump, three circulation pumps are required to operate the entire heating system, see Figure 1. The electrical power consumption of these circulation pumps is considered in the SPF but not in the SCOP, see equation 1 and equation 2. Therefore, the SCOP must always be greater than the SPF.

In Use Case A, the SCOP ranges from 4.15 to 4.25, while the SPF ranges from 3.35 to 3.7. Both the SCOP and SPF fall within the same range as other heat pumps and heat pump systems (Brudermueller et al., 2025), (Minder et al., 2014). The difference between the SCOP and the SPF is larger in Use Case A than in the other Use Cases due to the energy required by the pump for regenerating the ice storage. All ice storage volumes in Use Case A are relatively small compared to the other use cases, so the ice storage in Use Case A must be regenerated more frequently. This results in an increased power consumption for the circulating pump and subsequently lowers the SPF. In Use Case B, the SCOP varies between 3.9 and 4.55 and the SPF between 3.8 and 4.4. For small ice storage systems, the efficiency values are lower than those for the larger systems. The optimal design for Use Case B is an ice storage with a volume of 10 m³ and an unglazed collector area for the regeneration of 20 m². In the case of lager ice storage volumes, the efficiency of the system experiences a slight decrease, however, it remains significantly higher than the ones in Use Cases A and C.

In Use Case C, both the SCOP and the SPF are significantly lower than those observed in Use Cases A and B. This discrepancy can be attributed to the high specific heating demand of the single-family house. Consequently, a high supply temperature of the heating water is necessary to meet these demands. This results in a lower COP for the heat pump in this particular application, consequently leading to a lower SCOP. In summary, the systems in Use Case C demonstrate suboptimal efficiency in comparison to the other systems. Furthermore, the substantial volume of ice storage in Use Case C, in conjunction with the larger hear exchanger, results in elevated pressure loss. Consequently, the necessary circulating pump energy in Use Case C is notably high. Therefore, the SPF values range from 2.6 to 2.8, which are considerably lower than those observed in the other Use Cases.

Furthermore, the simulation results indicate that an increase in the size of the ice storage does not necessarily correlate with a higher overall system efficiency. This can be attributed to the fact that larger systems require longer regeneration periods, which can lead to extended phases during which the SOC remains within the range between 0 and 1. In contrast, smaller ice storage systems are able to reach a fully charged state with an SOC greater than 1 more quickly. Under certain conditions, this can lead to higher overall system efficiency. To ensure optimal system performance, ice storage systems require precise coordination of all system components. In particular, the balance between ice storage capacity and the solar collector area for regeneration plays a critical role in achieving high overall system efficiency.

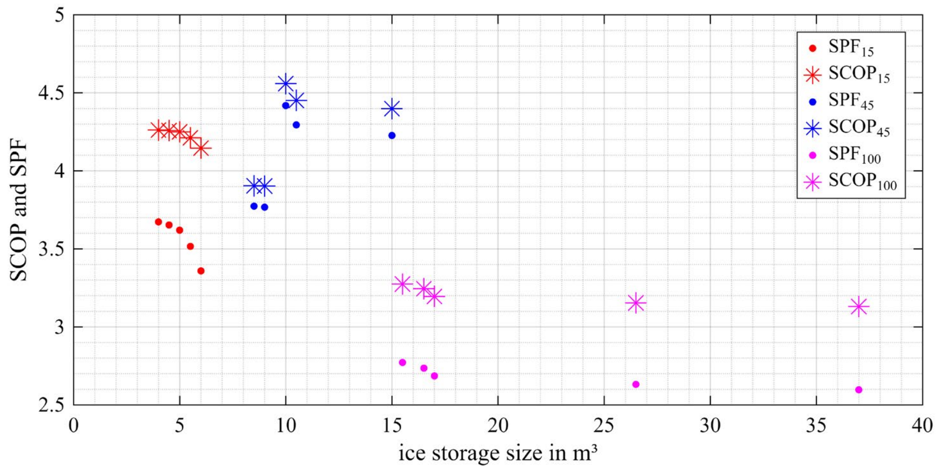

Figure 8: SCOP and SPF of all system configurations

4. Conclusions and Outlook

The present study investigated the performance of ice storage systems integrated into a combined heat pump and solar thermal setup through dynamic simulations conducted in MATLAB/Simulink using the Carnot Toolbox. By systematically varying ice storage sizes and solar collector areas across three distinct building energy standards, the aim is to determine the optimal system configuration of the ice storage and the necessary solar collector area for regeneration.

The simulations demonstrated that both the building's specific heating demand and the solar collector area strongly influence the required ice storage volume and the system's overall performance. In energy-efficient buildings (Use Case A), relatively small ice storage volumes between 4 m^3 and 6 m^3 were sufficient, with strong linear dependence on the collector area. For buildings with medium and high energy demands (Use Cases B and C), the required ice storage volume increased substantially, though the correlation between storage size and collector area weakened due to more complex thermal interactions.

In regard to system efficiency, the Seasonal Coefficient of Performance (SCOP) and the Seasonal Performance Factor (SPF) underscored the dynamic relationship between ice storage capacity, regeneration potential, and building demand. The highest efficiencies were achieved in Use Case B, with SCOP values ranging from 3.9 to 4.55 and SPF values from 3.8 to 4.4. These results indicate an optimal balance between ice storage size and regeneration area. Conversely, Use Case C exhibited a significant decrease in both indicators due to a higher heating demand, resulting in an increased supply temperature and, consequently, a reduction in the efficiency of the heat pump and the overall system.

Overall, the findings reveal that increasing ice storage size does not inherently enhance system efficiency. Instead, an optimal configuration emerges from balancing the ice storage capacity with the available solar regeneration area and the building's thermal characteristics.

Building upon the findings of this study, future work will focus on a comprehensive techno-economic analysis of heating systems incorporating ice storage and heat pumps. Sensitivity analyses will be employed to evaluate and compare various economic and ecological key performance indicators, such as system efficiency, investment and operating costs, as well as CO_2 savings. The results will be compared with conventional heating systems to evaluate relative performance benefits and asses their suitability for wider implementation.

5. Acknowledgments

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