Ice Storage as a Sustainable Facility for the Future: Potential Analysis of Various Regeneration Methods

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Abstract. The stability of the renewable energy supply is affected by daily and seasonal fluctuations of sources such as sun, wind, and water. In this context, ice storage systems are a promising solution for buffering the aforementioned fluctuations. This work is an investigation of ice storage systems combined with three different regeneration sources: ambient air, solar energy, and geothermal energy. The study encompasses three distinct geographical locations, each characterized by a different climatic condition. These include an alpine region in Obergurgl, a temperate area in the Inn Valley region in Innsbruck, and a southern climate in Florence. A *MATLAB* simulation is employed to calculate the behavior of the ice storage system over the course of a year. This is done for each location with each of the regeneration methods to facilitate a comparative analysis of the effectiveness of the three regeneration methods under the different climatic conditions. It is determined that geothermal energy via deep drilling is especially suitable for colder regions such as Obergurgl and Innsbruck. The use of solar energy such as PVT collectors results in the greatest limitations, as the heat generated during the summer months cannot be dissipated. Furthermore, when comparing an ice storage system to a system where the energy supply is solely based on geothermal energy, it becomes evident that the ice storage system offers significant advantages in terms of space requirements and costs. The results of this thesis demonstrate the true potential of ice storage systems in terms of energy efficiency, economic viability, and spatial requirements.

Keywords: energy storage, ice storage system, heating & cooling

Introduction

The European Union aims to cover 100 % of its energy demand from renewable energy sources by 2050 (European Commission, 2021). However, the stability of the energy supply is affected by daily and seasonal fluctuations in renewable energy sources such as sun, wind, and water. To meet this challenge, it is essential to store excess energy. In this context, ice storage systems are a promising solution for ensuring a continuous and reliable energy supply. The building sector is responsible for 39 % of the carbon emissions worldwide (Altuntas & Erdemir, 2022). According to *Statistik Austria*, heating accounts for approximately 70 % of household energy consumption in Austria in 2023/2024 (Statistik Austria, 2025).

To advance the use of renewable energy in heating and cooling systems, ice storage systems present an attractive approach. Combining ice storage with a heat pump offers high storage capacity, minimal space requirements, and a reliable heat source (Carbonell et al., 2016). The ice storage system achieves high storage capacity by utilizing the phase change from water to ice and the substantial energy associated with the enthalpy of fusion. Furthermore, a constant heat source at or above freezing, even in sub-zero temperatures is ensured. The ice storage, buried underground, benefits from continuous geothermal energy (Goeke, 2019). Additionally, the system can be regenerated using various renewable sources. This work specifically analyzes solar energy, geothermal energy, and ambient air as regeneration methods. Nevertheless, such systems are scarce in Austria, and there are currently no available tools for the dimensioning of ice storage systems and the consideration of optimal regeneration sources. This study considers the actual potential of an ice storage system concerning energy efficiency, economy, and space requirements.

Methodology

To evaluate the potential of an ice storage system combined with different regeneration methods, a simulation in *MATLAB* is conducted. The main aspect is to simulate the behavior of an ice storage in combination with a ground source heat pump and a regeneration source, as shown in the functional diagram in Figure 1. Three renewable energy sources are considered as regeneration methods: ambient air, solar energy, and geothermal energy. The simulation is performed separately for each regeneration source. The heat pump withdraws heat from the ice storage for heating and cooling of the building, whereas the regeneration source introduces energy into the ice storage preventing the ice storage from freezing completely. To protect the ice storage shell, a maximum of 70 to 90 % of the water may be formed to ice (ECOTHERM Austria GmbH, 2020; Lehmkuhl, 2021).

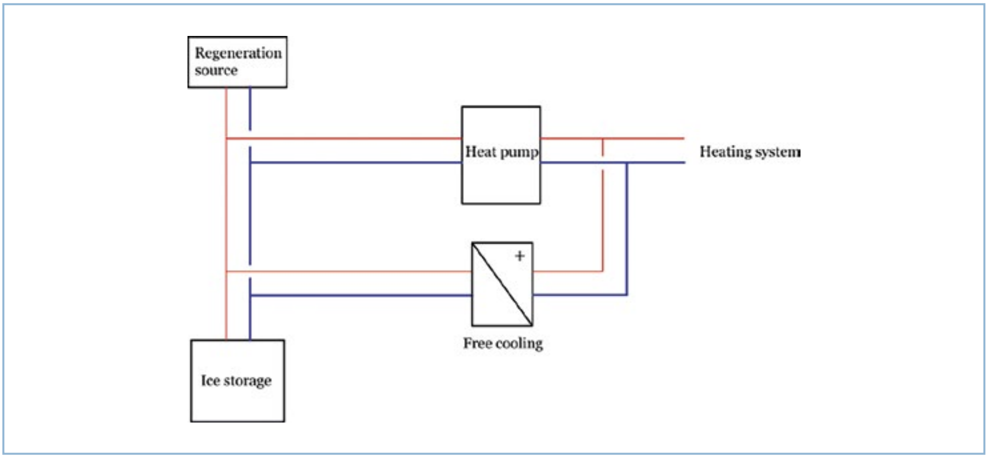

Figure 1: Functional diagram of the project with its four main components: ice storage, regeneration source, heat pump and heat exchanger for free cooling. Source: Author's own representation.

To assess the adaptability of the ice storage system to different climatic regions, the same building design (ground area 3 440 m^2) is simulated in three distinct locations:

- Obergurgl, an alpine region,
- Innsbruck, located in the Inn Valley,
- Florence, a warmer region selected for contrast.

A separate simulation of the building was conducted to generate climate data for the three locations. The extracted data includes hourly values over a full year, representing the average climate conditions of the past ten years. Key parameters such as outside temperature, solar radiation on the roof, and heating and cooling demand were derived from this dataset for further analysis. This data, along with the heating and cooling limits defined by ÖNORM B 8110-5:2011, serves as the basis for the simulation.

The simulation setup for the ice storage system is designed to enable both the heating and cooling of a building. The operational mode depends on various factors, including ambient temperature, the temperature of the ice storage, the percentage of ice present, and the availability of a regeneration source. The simulation is initiated with the ice storage as its point of origin. The ice storage is conceptualized as a system with defined boundaries. All heat flows entering and leaving the ice storage are analyzed in detail. The regeneration of the ice storage is influenced by several factors, such as its current state, the time of year, and the specific circumstances of each case. In order to maintain optimal conditions, the regeneration is either implemented into the ice storage or set to zero. The primary objectives are to ensure that the percentage of ice peaks at around 80 % and to keep the temperature of the ice storage below 18° C. The three different regeneration methods, implemented as dry cooler, deep drilling and PVT collectors, are analyzed separately for each location.

A key component of the ice storage system is the ground source heat pump, selected based on the heating load of the building, which varies across the three locations. Since the ice storage temperature drops to 0°C, the capacity of the heat pump at this brine temperature is of paramount importance. The model chosen for all locations is the TERRA SW MAX from iDM Energiesysteme GmbH and its data is implemented into the simulation.

Results and Discussion

This section presents the results of the ice storage behavior over one year, including ambient temperature, ice storage temperature, and ice percentage, plotted throughout the year. The simulation has been verified and validated for reliability and accuracy, although some simplifications mean a deviation from real-world conditions.

A comparative analysis of the locations reveals that, in general, the volume of the ice storage is greater in regions with lower ambient temperatures. However, the size of the ice storage is also dependent on the regeneration method employed. The net volumes of water range from 145.7 m^3 in Obergurgl, which uses a dry cooler, to 18.8 m^3 in Florence, which utilizes deep drilling. The net volume of water, and thus the storage capacity, is highest for each regeneration method in Obergurgl. Given that the costs of the ice storage itself represent most of the investment costs, it can be seen that the costs are also the highest for dry cooler and PVT collectors in Obergurgl in comparison to the other locations. For the deep drilling case, the highest costs occur in Florence. The investment costs vary between 89 100 € in Florence using deep drilling as regeneration method and 38 900 € also in Florence using a dry cooler. These findings are presented in Table 1. While the ice storage temperature in the deep drilling case in Florence remains below 18°C, it is evident that the high investment costs are not economically viable. In a southern and warmer climate, alternative systems, such as an air-source heat pump, are likely to offer a more cost-effective and efficient solution than an ice storage system.

Table 1: Summary of the results including regeneration power, net volume, storage capacity and investment costs for each location and each regeneration source. Data source: Author's own simulation.

Parameters	Unit	Obergurgl	Innsbruck	Florence
Ambient air – dry cooler				
Regeneration power	kW	15	15	15
Net volume	m^3	145.7	88.1	20.6
Storage capacity	kWh	13 188	7 977	1 865
Investment costs	€	80 900	60 800	38 900
Solar energy – PVT collectors				
Regeneration power	kW	15.9	13.5	6.68
Net volume	m^3	126.8	79.0	22.7
Storage capacity	kWh	13 188	7 977	1 865
Investment costs	€	81 200	64 000	40 300
Geothermal energy – deep drilling				
Regeneration power	kW	6.4	6.4	19.2
Net volume	m^3	87.9	44.4	18.8
Storage capacity	kWh	7 957	4 019	1 703
Investment costs	€	77 000	60 600	89 100

In order to facilitate a comparative analysis of the regeneration sources in each location, the annual courses of the ice storage temperature and the percentage of ice over the course of the year are plotted. The results for each location and two of the regeneration methods, namely deep drilling and PVT collectors, are presented in Figure 2. As illustrated in the plots, the curves demonstrate distinct outcomes for each location, particularly with regard to the two regeneration sources. The maximum ice content is set to approximately 80 % for each case. Additionally, the objective is to maintain the ice storage temperature at a maximum of 18° C. As illustrated in the plots of the deep drilling regeneration method, the maximum temperature is approximately 18° C. Conversely, when considering PVT collectors as a regeneration method, the maximum temperature is undershot in Obergurgl. In Innsbruck and Florence, the temperature is exceeded significantly. This is due to the fact that with PVT collectors, dissipating heat in the summer is a considerable challenge.

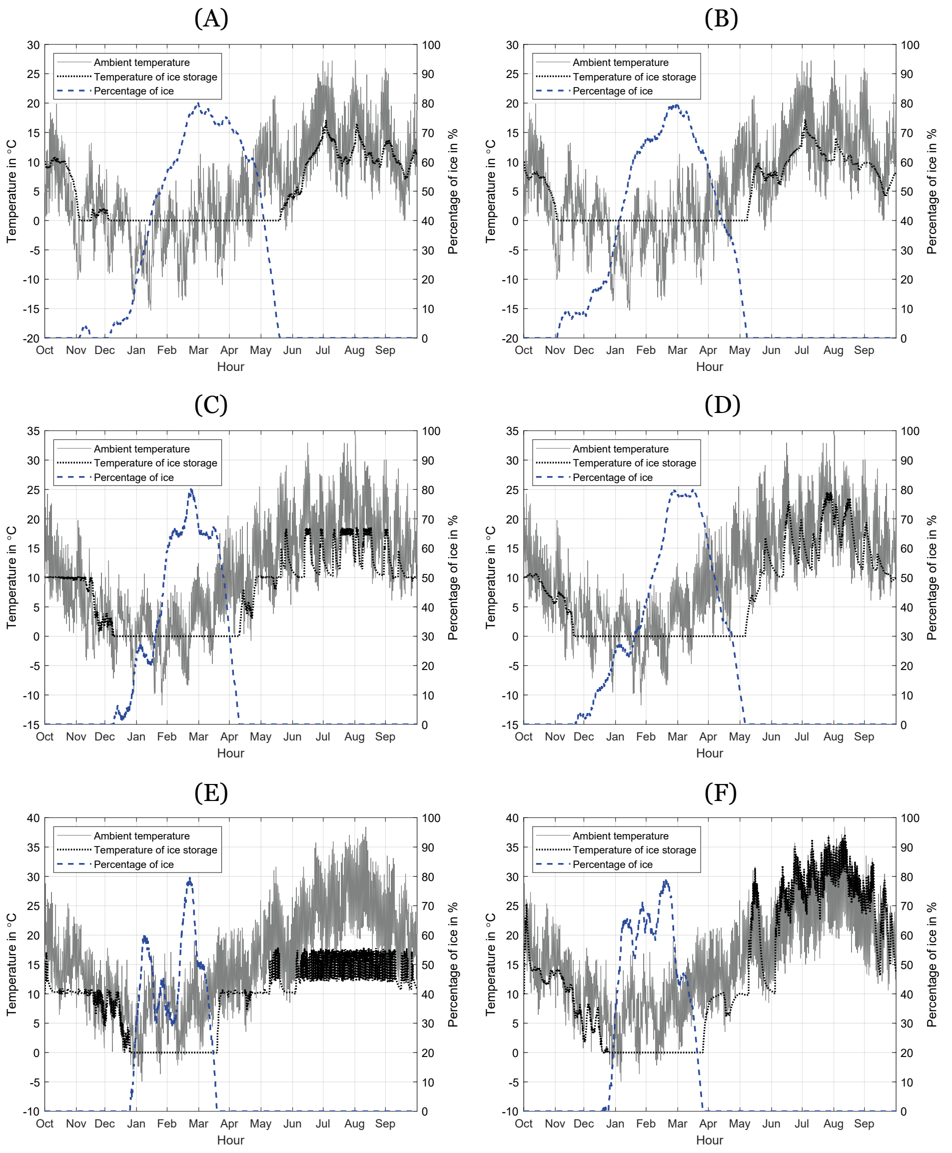

Figure 2: Deep drilling in Obergurgl (A), Innsbruck (C), Florence (E) and PVT collectors in Obergurgl (B), Innsbruck (D), Florence (F). Source: Author's own simulation and representation.

Another key objective of this study is to compare the performance of the ice storage system using geothermal energy as a regeneration source with that of a system relying solely on deep drilling combined with a ground-source heat pump. In the latter case, the required number of boreholes increases significantly, leading to considerably higher investment costs.

Conclusion and Outlook

The simulation created in this work, incorporates climate data and building energy demands and demonstrates that ice storage systems are particularly effective in colder regions like Obergurgl and Innsbruck, where geothermal energy from boreholes represents the most efficient and cost-effective regeneration method. In warmer climates such as Florence, a dry cooler may be the most cost-effective regeneration solution. However, the higher ambient temperatures make Florence generally less suitable for ice storage systems. The growing significance of renewable energy sources suggests that ice storage systems will become increasingly popular, offering substantial storage capacity and efficiency benefits. Current projects in Tyrol, including one by the Austrian Armed Forces and a hotel utilizing both geothermal energy and ice storage, highlight the system's potential. Furthermore, the applicability of an ice storage to balance peak loads in municipal energy networks points to its promising future.

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