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# Effect of climate on the optimal sizing and operation of seasonal ice storage systems

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**Abstract.** Seasonal thermal storage systems can reduce the temporal mismatch between renewable energy availability and energy demand. Ice storage systems exhibit a non-linear behaviour in the heat exchange and storage processes, complicating the formulation of optimal design and operation problems. In this work, we propose a mixed-integer quadratically-constrained programming formulation, which minimizes the Levelized Cost of Energy for space heating and cooling, including sizing of a supporting PV array. The optimization was repeated for different storage volumes, finding the system optimal operation in each case –and thereby the optimal system sizing. The heating and cooling demands were computed from an archetypal office building, placed in three reference locations with cold and semi-arid, warm and humid continental, and temperate and humid continental climates. Results show that the optimal PV size decreases with growing ice storage volume, and an ice storage works best in a temperate continental climate, covering up to 47% of the cooling demand with a 250 $m^3$ storage.

## 1. Introduction

Seasonal thermal storage systems can reduce the temporal mismatch between periods with high renewable energy generation and periods with high energy demand. In heating-dominated climates, this means storing excess generation or waste heat during summer, to be used later in winter [1]. Ice storage systems can perform this task, serving as a heat source during the heating season, and providing free space cooling during summer. The high latent heat of fusion of water allows storing a high amount of energy in a small volume, which makes these systems attractive. Despite the available literature on monitoring and/or simulation of ice storage systems (e.g. [2]), there is a clear gap in the formulation of an optimization framework for selecting the optimal size and operation of seasonal ice thermal storage systems. Moreover, there is a lack of sensitivity studies that assess the techno-economic performance of these systems in different climates.

## 2. Optimization model

This Section describes the constraints and the objective function of the optimization problem.

### *2.1. Ice storage*

A time-varying binary variable $s(t)$ is employed to model the heat balance occurring during the phase-change and the liquid state: if the storage temperature is higher or equal to the melting temperature $T_f$, the ice storage is operating in its sensible range and $s(t) = 1$. Vice versa, when the temperature is lower or equal to the melting temperature, the storage is operating in its latent range and $s(t) = 0$. Two energy balances are employed, based on the value of $s$. When the storage is operating in its latent range, the heat exchange does not affect the storage temperature $T$, but affects the amount of water in the storage, $\epsilon$, which can vary between 0 (all ice) and 1 (all water). This process is modelled in Eq. (1).

$$s(t) = 0 \implies \begin{cases} T(t) \leq T_f, \\ T(t) = T(t-\Delta t), \\ \rho_i V_{st} h_f \frac{\epsilon(t)-\epsilon(t-\Delta t)}{\Delta t} = \sum\limits_{u \in N_u} P_u(t) - \sum\limits_{d \in N_d} P_d(t) - UA_{st}(T(t) - T_g) \end{cases} \tag{1}$$

$$s(t) = 1 \implies \begin{cases} T(t) \geq T_f, \\ \epsilon(t) = \epsilon(t-\Delta t), \\ \rho_w V_{st} c_{p,w} \frac{T(t)-T(t-\Delta t)}{\Delta t} = \sum\limits_{u \in N_u} P_u(t) - \sum\limits_{d \in N_d} P_d(t) - UA_{st}(T(t) - T_g) \end{cases} \tag{2}$$

Where $N_u$ and $N_d$ are the energy system branches connected upstream and downstream of the storage of volume $V_{st}$. The heat transfer coefficient of the storage is $UA_{st}$, and we assume that all the heat gains come from the surrounding ground at temperature $T_g$. As we assumed that once the water in the storage is completely frozen, ice cannot be cooled further (i.e. below $0°C$), $\epsilon(t) = 0$ represents the maximum state of charge of the ice storage, and heat cannot be further extracted from the storage. When $\epsilon(t) = 1$, the storage is full of water and operating in its sensible range, and if heat is supplied to it, the water temperature increases. This process is represented by Eq. (2). A constant value was used to determine the maximum heat transfer coefficient of the storage. One additional constraint is considered to avoid overestimating the heat rejected in the ice storage through a bypass pipe, which limits the free cooling to the latent heat stored in the remaining ice in the storage (Eq. (3)):

$$P_u(t) \leq \rho_i V_{st} h_f (1 - \epsilon(t)) \tag{3}$$

Lastly, two constraints are employed to ensure a cyclical behaviour of the storage, forcing that both the storage temperature and ice level are equal at the beginning and at the end of the year.

### *2.2. Heat pumps and chillers*
Heat pumps and chillers were modelled assuming that the inverse of their COP is a linear function of the heat source (heat sink) temperature. Thus, Eq. (4) was employed to model their performance using $c_0$ and $c_1$ coefficients obtained with a linear regression:

$$P_{el,hp}(t) = P_{th,hp}(t)(c_0 + c_1 T_{hs}(t)) \tag{4}$$

where $T_{hs}$ is the heat source (sink) temperature. In the case of air-source heat pumps and air chillers, $T_{hs}$ is a known variable (outdoor air temperature). In the case of the water-to-water heat pump extracting heat from the ice storage, $T_{hs}$ coincides with the storage temperature, which is an optimization variable. In such a case, Eq. (4) becomes a quadratic constraint.

### *2.3. PV systems*
The efficiency of the PV system was modelled with the correlation shown in Eq. (5):

$$\eta_{pv} = \eta_{ref}[1 - \beta_{ref}(T_c - T_{ref})] \tag{5}$$

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where the cell temperature $T_c$ was calculated using the correlation proposed by Duffie and Beckman [3], which depends on air temperature, wind velocity, nominal operating cell temperature and incident global solar radiation on the PV modules.

*2.4. Objective function*
The objective function to be minimized was formulated as in Eq. (6):

$$f = \sum_{n=1}^{nn} V(n)i(n) + \sum_{t=1}^{H} \lambda_{imp}P_{imp}(t) - \lambda_{exp}P_{exp}(t) \quad (6)$$

where $n$ is the component on the n-th node of the energy system, $V$ and $i$ are the corresponding size and specific investment cost. Thus, the first term in Eq. (6) corresponds to the investment cost of the energy system. The second term represents the annual operating costs, where $\lambda_{imp}$ and $\lambda_{exp}$ are the prices associated with imported and exported electricity.

## 3. Methods
*3.1. Case study*
Three reference locations were chosen, each belonging to a different climatic zone according to Köppen-Geiger classification [4]: Denver (CO), Buffalo (NY) and International Falls (MN). Denver, close to the Rocky Mountains, features a semi-arid climate (BSk). Buffalo has a humid continental climate (Dfb/Dfa) with snowy winters due the proximity of Lake Erie. International Falls has a humid continental climate (Dfb), with long cold winters and warm humid summers. The specific locations have been chosen as they could be suitable for ice storage applications due to a combination of cold winters and warm summers.

The energy demand for space heating and cooling was obtained by simulating the reference small office archetype building provided by the Office of Energy [5] with EnergyPlus using the weather files of the locations mentioned above. It was assumed that one storage would serve five buildings to justify the investment in the seasonal ice storage systems.

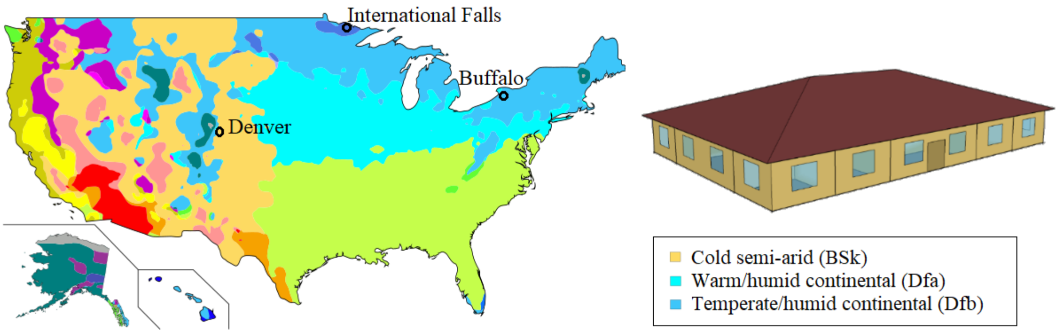


**Figure 1.** Climatic zones across the US and case study building.

*3.2. Main assumptions*
Results strongly depend on the correlations used for describing heat pumps' and chillers' performance, namely $c_0$ and $c_1$ in Eq. (4). The values assumed here were obtained by regressing the correlations proposed by Staffell et al. [6] for heat pumps ($c_0$ = 0.2384 and $c_1$ = -0.00308) and by Joe and Karava [7] for chillers ($c_0$ = 0.09913 and $c_1$ = 0.006571). The hourly profiles of air temperature, heating and cooling load were resampled using a time-step of 8 hours, which

allows for a reduction in the number of decision variables of the optimization problem while capturing intra-day variations of the boundary conditions. The cost of the ice storage was taken from Allan et al [8] considering a lifetime of 50 years. For heat pumps and chillers, a fixed cost of 576 €/kW was considered over a lifetime of 20 years [1]. Electricity prices are 0.238 €/kWh for imported electricity and no reward is associated with electricity export.

### *3.3. Workflow*
The optimization was formulated using the constraints and the objective function described in Section 2, aiming at finding the best size of the energy converters (PV systems, heat pumps and air chiller) for a given size of the ice storage within the energy system shown in Fig. 2. Six optimization runs were carried out for each climate: one run without ice storage, and five runs considering storage systems of sizes between 50 and 250 $m^3$. The quadratic constraints in Eq. (4) make the problem a Mixed Integer Quadratically-Constrained Problem (MIQCP), solved using Gurobi 10.0 [9] and *gurobipy* with a MIPGap of 1% as the exit criterion.

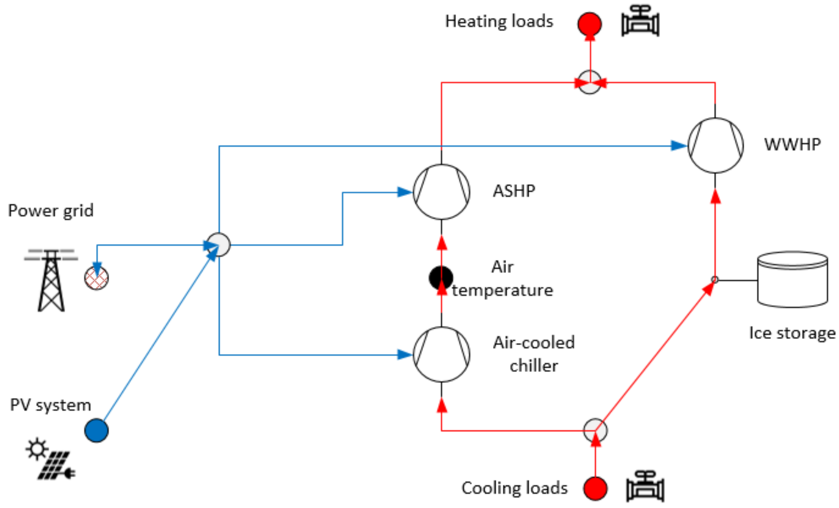


**Figure 2.** Qualitative energy system schematics including the ice storage.

## 4. Results
This section presents the outputs of the optimizations performed. Figure 3(a) shows the optimal ice level and water temperature for the case study buildings in Buffalo, assuming an ice storage of 150 $m^3$. This figure shows that the water in the storage starts freezing in January, and in late March the water is fully frozen. Water freezing is achieved by operating the water-to-water heat pump (WWHP), as shown by the green curve in Figure 3(b). Buffalo's rigid winter, with temperatures often below the melting temperature $T_f = 0°C$, helps make the WWHP a more efficient heating solution compared to the air-source heat pump (ASHP), which runs when air temperatures exceed this value -see the blue line in Fig. 3(b).

The ice level is kept close to 100% during spring. Then, when summer begins, the ice is used to efficiently cover some of the cooling demand. In general, the air chiller supplies the base cooling load, while peak loads are covered by the ice storage. In this way, the ice storage also reduces the needed chiller capacity, thus reducing the investment costs. At the beginning of October, the ice is fully melted and the water warms up until approximately $4°C$. In the remaining parts of the year (November and December), the WWHP extracts heat from the

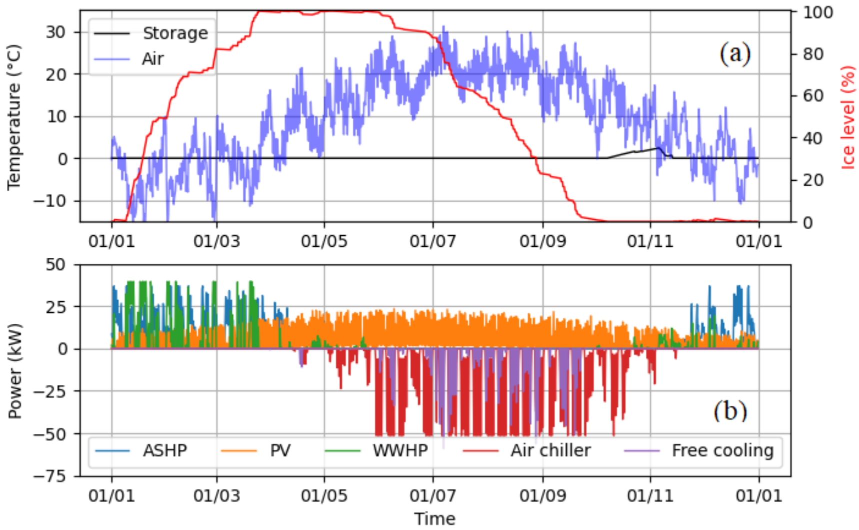


**Figure 3.** Optimal operation of a 150 $m^3$ ice storage in Buffalo: (a) ice level, temperature and (b) power profiles.

storage, thus reducing the storage temperature to approximately $0°C$. The ground tends to heat the storage, but a few operations of the WWHP are sufficient to maintain the temperature around $0°C$. Most of the heating load during these months is provided by the ASHP.

A similar system control behaviour was found in the other climates considered. Climate affects both the performance of air-source heat pumps and chillers, as well as the heating and cooling demands of the case study buildings. In Figure 3, which refers to the 150 $m^3$ ice storage in Buffalo, the storage covers 14.8% of the cooling load and 53.4% of the heating load. Figure 4(a) shows that Buffalo is the location with the lowest share of cooling demand supplied by the ice storage, whereas Figure 4(b) shows that it is also the case study with the highest heating coverage. Furthermore, in Buffalo, the optimal solution requires a larger PV array compared to the other climates. For the intermediate storage size (150 $m^3$), the optimal PV array is 27.3 $kW_p$, compared to 23.5 $kW_p$ in Denver and 18.3 $kW_p$ in International Falls.

The optimal PV size decreases with growing ice storage volume, as shown in Figure 4(c). This is probably due to the optimizer trying to minimize electricity imports by maximizing the PV self-consumption. The bigger the storage, the lower the contribution that PV systems can give to achieve maximum self-consumption, but at the same time the higher the amount of free cooling available during summer. For this reason, the case study of International Falls is the one showing the most promising results: 27.8% of the cooling load can be supplied by the 150 $m^3$ ice storage, and the ratio increases up to 46.9% when the biggest size (250 $m^3$) is considered.

This is confirmed by the fact that the Levelized Cost of Energy (LCOE) with ice storage, especially for big volumes, is comparable with LCOE without ice storage -as shown by the blue line in Figure 4(d). The same is not true for big ice storage systems in Denver and Buffalo, where big ice storage systems tend to significantly increase the LCOE. Despite Buffalo being the second coldest location among those considered, results show that it entails the lowest free cooling ratio, the highest nominal power of the PV system and the highest LCOE. The offices in Denver, which have higher cooling demand and lower heating demand compared to Buffalo, show a better performance with regard to all the mentioned indicators.

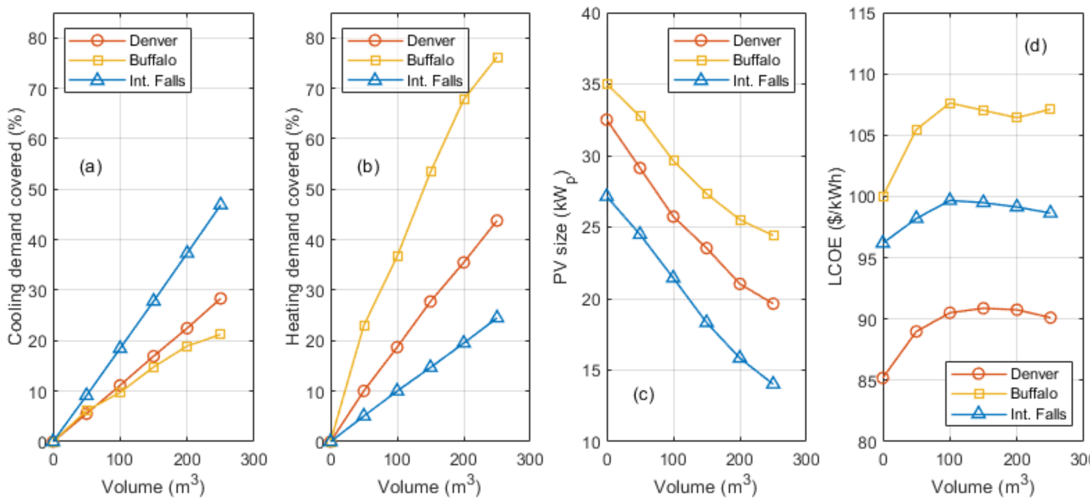


**Figure 4.** (a) Cooling and (b) heating supplied by the storage, (c) PV size and (d) LCOE.

## 5. Conclusions

A mixed-integer quadratically constrained problem was formulated to find the optimal design and operation of an energy system consisting of an ice storage, a PV system, an air source heat pump, a water-to-water heat pump and an air chiller. The case study consists of five small office buildings located in three cities in the U.S. characterized by different climates. Results showed that the local climate conditions have a strong influence on the key performance indicators. The optimal PV system size decreases with increasing ice storage volume. With the considered boundary conditions (capital cost, electricity price and energy demand), the best option is a system without ice storage. Nevertheless, this study provides a methodology that, assuming different boundary conditions, could identify the optimal sizing and operation of the system.

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