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Investigating the Performance of a Seasonal Cold Storage System for Dry and Mountainous Climates

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Abstract:
Seasonal cold storage presents an eco-friendly and highly efficient solution for capturing natural or artificial cold energy during winter, which can then be utilised for cooling during summer. This research proposes an innovative cold storage system tailored for mountainous climates. The system harnesses refrigeration technology and cold ambient air to produce ice, offering a sustainable approach to glacier recovery. Additionally, the stored water within the ice storage system reduces surface water evaporation in arid, high-altitude regions. In this study, we detail the performance of the proposed system and examine its effectiveness using climate-specific equations for the Tafresh region. The system operates with a 5 kW refrigeration cycle and fans to direct cold air into the storage compartment at optimal speeds when the ambient temperature reaches -3°C. For the case study presented, the system not only decreased energy consumption by 13.73% during the summer months and reduced operational costs by 8%, but it also conserved 150 m³ of water, transferring it from the rainy season to the warmer months. Furthermore, the system successfully achieved peak load shaving of 2 kW during peak demand periods. This study highlights the system's dual benefits in energy conservation and water management, making it a compelling solution for sustainable cooling in mountainous regions.

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1. Introduction

The global demand for cooling has increased significantly in recent decades due to population growth, industrial advancements, widespread use of electronic equipment, modern construction technologies, and the rise in global temperatures. The continuous increase in average global temperatures, largely driven by the excessive consumption of fossil fuels, has led to the rapid depletion of natural glaciers. This alarming trend has motivated a shift toward alternative, sustainable energy solutions. Seasonal cold storage presents a promising method to both revive glaciers and reduce energy consumption. In regions facing water scarcity, particularly in Central Asia, seasonal cold storage can play a vital role in crisis management by preserving water that would otherwise evaporate during winter in the form of ice. Additionally, this system aims to decouple energy consumption during peak summer hours, ensuring a continuous balance of electrical energy demand.

Research on seasonal storage systems has focused on two main objectives: storing heat during the summer for use in winter [1-3], and storing cold during winter for use in summer, the latter being the focus of this study. The viability of such systems depends on several parameters, including climatic conditions, economic factors, energy tariffs, and the operational demands of buildings and their ventilation, heating, and cooling systems [4]. Traditional cooling systems rely heavily on thermal and electrical equipment, resulting in high levels of fossil fuel consumption. In contrast, seasonal cold storage, which captures cold energy in the winter and stores it for summer cooling, significantly reduces fossil fuel reliance [5].

Seasonal storage, though a concept with deep historical roots, has evolved considerably over the years. Since the 1970s, modern seasonal cooling storage systems have been developed, incorporating a wide range of methods. The oldest and simplest approach involves collecting snow and

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ice during winter and using it for cooling in the summer. While effective, this method is costly, requiring extensive equipment and labour for snow and ice collection. Moreover, impurities and contaminants in collected snow and ice can damage water pipes [6].

In contemporary systems, cooling energy is typically produced using advanced technologies such as snow guns, heat exchangers, or heat pipes. For instance, in 2002, Skogsberg [7] investigated a seasonal snow cooling system at Sundsvall Hospital in Sweden. In this system, snow was generated using snow guns, where water and air are sprayed separately under pressure and mixed in cold air, resulting in snow production. The system achieved an energy effciency of up to 92% as the storage expanded, with 1 to 3 kWh of energy consumed per ton of snow.

Other innovative systems have been developed over the years. In 2016, Yan et al. [5] designed a hybrid system in China that utilises an evaporator and condenser to store cold energy. The upper portion (condenser) is exposed to the cold outside air, while the lower portion (evaporator) is submerged in an underground water reservoir. Although this system has a higher initial cost, it does not require additional energy during operation. Similarly, the Icebox project in Canada, researched by Clasen in 1981 [8], and the work by Francis and Tamblyn [9], both employed outdoor cold air to freeze water into layers of ice, achieving efficiencies between 90-100%.

Several other studies have focused on improving cold storage performance through various means. For example, Ardehali [4] explored cold energy storage using water, ice, and eutectic salts, while Elwan et al. [10] modelled heat transfer in freezing systems. Singh et al. [11] studied cold seasonal storage using heat pipes to control data centre cooling, and Popov et al. [12] reviewed energy-efficient seasonal storage systems using heat pipes. Additionally, Yan et al. [13] developed a hybrid system combining ice and cool water storage, resulting in a 40% increase in the lifecycle of the stored water. Economic analysis of seasonal cold storage systems is also crucial, as Persson and West Mark [14] demonstrated their cost-competitiveness with conventional methods. Singh et al. [15] evaluated the performance of thermal control systems using heat pipes.

Kranz and Frick [16] conducted a study on the use of Aquifer Thermal Energy Storage (ATES) to provide efficient cooling for large buildings, specifically using the German Parliament Buildings as a case study. They found that over a period of nearly 10 years, the system achieved a Coefficient of Performance (COP) ranging from 3.6 to 7.8. Their findings suggest that the efficiency of ATES systems can be further improved by optimizing operational parameters such as the cooling network's temperature and the regeneration temperature of the storage. This indicates the potential of ATES systems to enhance energy savings and cooling efficiency in other similar projects.

Hamada et al. [17] explored the integration of a hybrid system for snow storage and air conditioning in Sapporo, Japan. This system used renewable energy for snow storage and melting, combined with space cooling through cryogenic energy from stored snow. Field measurements showed that the system provided up to 74% of the cooling needs on the first day of operation during the cooling period, closely matching predictions. The authors demonstrated the system's ability to conserve energy and reduce environmental impact under severe winter conditions, which underscores its potential for use in cold regions with abundant snowfall.

Zhang et al. [18] introduced a low-cost seasonal solar soil heat storage system designed for greenhouse heating. Their pilot study revealed that the system effectively stored solar heat in the soil during warmer periods and released it during colder seasons, maintaining optimal greenhouse temperatures without relying heavily on conventional heating systems. The system's success in reducing heating costs and energy usage presents a sustainable alternative for managing greenhouse climate control, particularly in regions where solar energy is abundant.

Yang et al. [19] conducted simulations and experimental validations of a soil cool storage system that utilizes natural energy. Their work showed that soil could serve as an efficient medium for storing cold energy during winter for use in cooling buildings during warmer months. This study demonstrated significant potential for energy conservation by reducing reliance on conventional air conditioning, supporting the broader application of seasonal energy storage in building energy management strategies.

Despite these advancements, there remains a significant research gap in the optimisation of seasonal cold storage systems for specific climates, particularly in regions with cold, mountainous conditions and high summer temperatures, such as Central Asia and Iran. Most existing studies have focused on energy efficiency and economic viability, with limited attention to water conservation and glacial recovery as primary objectives.

The novelty of this study lies in the development of a seasonal cold storage system that prioritises water storage as the primary objective, with cool energy storage as a secondary goal. The proposed system addresses the unique challenges of mountainous climates, where both water scarcity and high cooling demand are pressing concerns. Additionally, this system aims to aid in natural glacial recovery, a critical environmental issue. The system integrates two main cooling sources: ambient cold air, circulated via fans, and a refrigeration cycle that transfers cooling energy to the ice storage. This dual-source approach offers a new method for reducing both energy consumption and water evaporation in regions facing extreme seasonal variations. Furthermore, this paper provides a detailed model of the system, including thermal dissipation calculations and refrigerant charge fatality, filling a critical gap in the current literature on cold storage system optimisation for water conservation and energy efficiency in challenging climates.

2. Modeling the Cold Storage System

2.1. Climates

In this research, the climate of Tafresh, located in the Markazi province of Iran, is thoroughly examined. Tafresh is situated in a mountainous region, making it an ideal location for studying cold storage systems. Based on climate data from the past few decades, Tafresh is classified as a cold and semi-arid region, characterised by significant seasonal temperature fluctuations [20]. Based on the Electric Power Industry Statistics IRAN report, Tafresh, with its reliable power infrastructure and energy distribution network, is a suitable location for implementing cold storage technologies [21].

Figure 1 illustrates the monthly average temperatures of Tafresh since 2016, revealing that February consistently experiences the lowest average temperatures. This makes February the optimal month for ice production, as the cold conditions during this period offer the greatest potential for efficient seasonal cold storage.

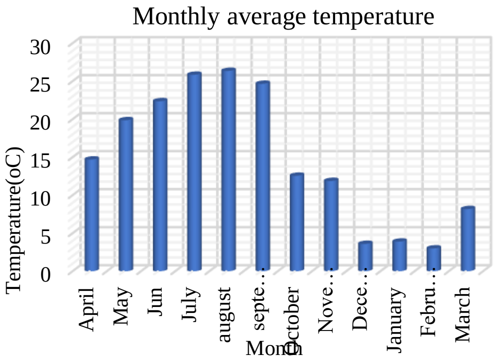

Figure 1. Average temperature in months of the year

2.2. System Design

Figure 2 presents a schematic representation of a dynamic cold storage system, consisting of two primary components: ice production and storage. The system is equipped with various elements, including multiple fans, thermometers placed at both interior and exterior points, a perimeter surrounding the ice production and storage areas, cold air ducts, and insulated compartments designed to store snow. Additionally, the system includes plates for ice formation and water sprays to facilitate the freezing process. In this system, the cooling mechanism operates by transferring cold air over the water in the reservoir and through the ice plates, efficiently producing and maintaining ice within the storage compartment. The integration of these components ensures that cold energy is effectively generated and preserved for future use.

In the proposed system, the cooling process begins when the outside air temperature falls below 0°C. Specifically, when the thermometer at the cold air inlet detects temperatures lower than -3°C, the fans are activated to increase airflow, thereby accelerating the freezing process. Cooling is further enhanced by water sprayed onto the plates, aiding in ice formation. One of the key objectives of this system is to maintain the ice produced during the winter through the end of the warm months. Another important consideration is the placement and design of the ice storage reservoir.

The ground temperature in summer is consistently lower than the air temperature, and the depth at which the reservoir is located significantly influences temperature variations. The primary factor affecting cooling load losses is the ambient temperature surrounding the reservoir. To minimise energy loss, the reservoir is embedded in the ground, with only the upper surface exposed to warmer air. This strategic positioning helps retain the stored ice by limiting heat transfer from the surrounding environment.

In cities where outdoor temperatures frequently drop below -3°C, cooling can be supplied solely through fan-driven air circulation and natural processes. However, in areas where such conditions are not prevalent, the refrigeration cycle serves as an additional source of cooling energy.

As the cooling process continues and water turns into ice at sub-zero temperatures, heat transfer from the ground becomes a critical parameter. Once the water reaches 0°C and begins to solidify, the ice must be cooled further to ensure greater resistance to melting. The final temperature of the stored ice depends on various factors, including environmental conditions, the type of insulation used, and the characteristics of the reservoir.

In this study, based on the climatic conditions and the system design, a storage temperature of -3°C was identified as optimal for maintaining ice throughout the warmer months.

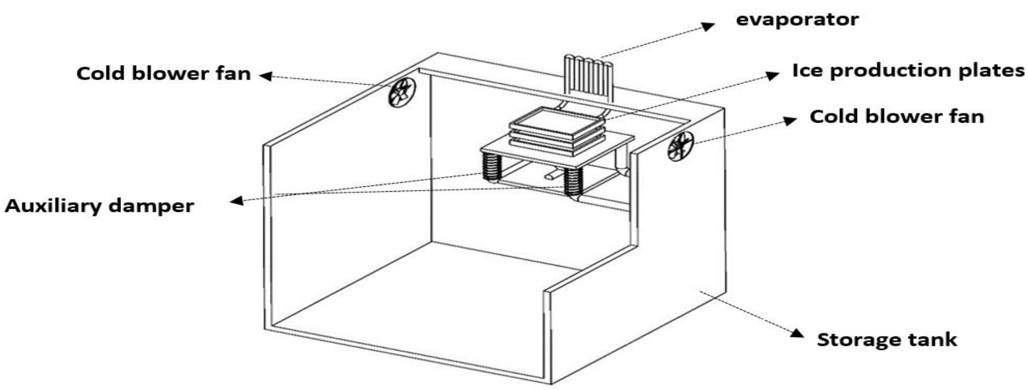

Figure 2. sketch of seasonal ice storage system

2.3. Governing Equations

In this study, the thickness and mass of the ice are calculated transiently using established equations. The ice formation is assessed in small time intervals, allowing for a step-by-step accumulation of ice mass over time. By summing the incremental ice formations over these short periods, the total rate of ice production is determined. The following section outlines the algorithm used to model and compute the ice production process.

2.4. Algorithm of the Calculation Process

As depicted in Figure 2 and explained in the equations section, when the ambient air temperature falls below -3°C, the cooling energy for the system is provided by both the refrigeration cycle and fan-assisted airflow. However, when the temperature sensors detect ambient air above -3°C, the cooling power is supplied solely by the refrigeration cycle. The ice formation process occurs in three stages: first, the water is cooled from its initial temperature to 0°C; second, the water at 0°C is converted into ice at the same temperature; and finally, in the third stage, the ice is further cooled to -3°C. The thickness of the ice and the time required for each stage are calculated to determine the total necessary cooling time and ice thickness.

2.5. Extraction Equations

Based on the provided explanation, the ice production system operates in two distinct modes:

- First Mode: Ice production occurs solely through the refrigeration cycle.
- Second Mode: Ice production is achieved through a combination of the refrigeration cycle and airflow assistance.

2.5.1. First Mode Calculations

In this case, the required time and mass of ice production are calculated in three distinct steps:

Step One: The fan does not circulate outside air over the pond. This mode is applied in environments where the temperature is above the freezing point, and ice production relies solely on the refrigeration cycle. The water enters the basin at an initial temperature higher than zero. The time required for the water to cool from its initial temperature, T_1, to the target temperature, T_2, is calculated as follows:

$$dt = \frac{m * c_w * (T_s - T_1)}{q} \qquad T_s = T_2 = T_1 + \frac{q * dt}{m c_w} \tag{1}$$

$$\Delta t = \frac{-m * l_f}{q} \tag{2}$$

Thickness and the mass of the arched ice at each stage are calculated as the following:

$$dm = \frac{-q * dt}{l_f} \tag{3}$$

$$dy = \frac{dm}{\rho_{ice} * A} \tag{4}$$

Stage 3: Once the total ice mass reaches its maximum value, the time required for the ice at 0°C to cool further to -3°C is calculated.

$$dt = \frac{m * c_{ice} * (T_s - T_1)}{q} \qquad T_s = T_2 = T_1 + \frac{q * dt}{m c_{ice}} \tag{5}$$

2.5.2. Second Mode calculations

When the ambient air temperature drops below -3°C, the fans installed above the water level in the reservoir increase air velocity, thereby enhancing convective heat transfer. As a result, the rate of ice production is significantly improved.

The cooling load between the flowing air and the water in the production tank can be calculated using thermal resistance, the convective heat transfer coefficient, and the temperature difference between the ambient air and the heat transfer surface. These factors play a crucial role in determining the efficiency of the ice production process. The relationship between the convective heat transfer coefficient and the fan speed can be expressed by the following formula [22]:

$$h_f = 10.45 - v + 10\, v^{1/2} \left(\frac{w}{m^2 k}\right) \tag{6}$$

This equation is applicable for airflow speeds ranging from 2 to 20 m/s. As illustrated in Figure 3, increasing the airflow speed up to approximately 15 m/s results in a significant enhancement of the heat transfer coefficient.

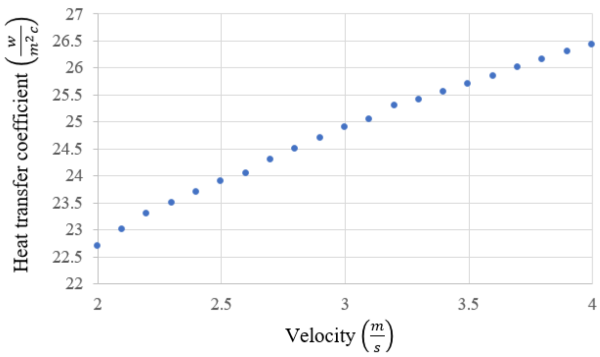

Figure 3. Heat transfer coefficient of displacement based on air velocity [21]

The second stage of the calculation follows a similar process as the first stage, with the key difference being that the total cooling time now accounts for both the refrigeration cycle and the fan-assisted cooling. In this case, the system benefits not only from the cooling load provided by the refrigeration cycle (q) but also from the additional cooling load generated by the fan (q'), as expressed in the equation below:

$$q' = \frac{T_{inf} - T_1}{\frac{1}{h_f * A}} \tag{7}$$

At any given time, the amount of heat loss from the reservoir is calculated. Since the tank is located underground, it is essential to determine the heat transferred from the tank walls to the surrounding soil. To compute the cooling energy dissipation, the following equation requires four key parameters:

$$Q = UA'(T_g - T_{tank}) \quad (8)$$

As the ground temperature fluctuates across different seasons, Equation 8 is employed to calculate the cryogenic charge loss. The overall heat transfer coefficient is determined by considering the materials used in the construction of the storage tank. Given that Tafresh experiences a cold and semi-arid climate, the variation in ground temperature throughout the year is depicted in Figure 4:

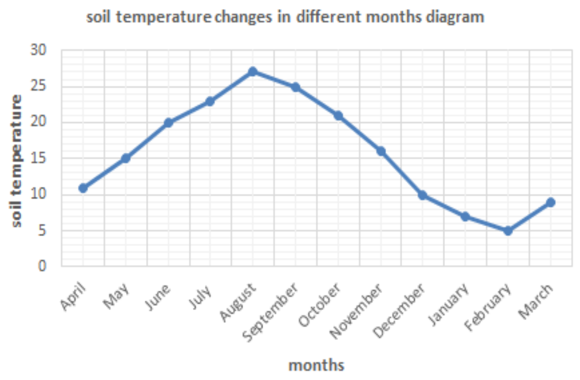

Figure 4. Soil (ground) temperature variation chart in months of the year

3. Results and Discussions

3.1. Performance of Cycle

In this study, the performance of the proposed system was evaluated for Tafresh, a dry mountainous city. The calculations are based on temperature data from the year 2016, recorded at 10-minute intervals. The system specifications used in this research are summarised in Tables 1 and 2.

Table 1. System specifications and storage tank wall assumptions

Parameters (units)	Values
Refrigerant load through system (q)- w	5000
Fan speed (v) - $\frac{m}{s}$	15
Overall heat transfer coefficient(U) $\frac{Btu}{m^2.c}$	0.159
Platform Area (A)- m^2	1
Water mass in tank (m)- kg	1
Temperature inside the Ice Storage Tank-(T_{tank}) - °C	-3
Heat transfer surface area $(\acute{A}) - m^2$	25

Table 2. Specifications of the storage tank septum

Materials	Thickness (cm)	Conductive heat transfer coefficient (W/m^2K)
Reinforced concrete	20	2.3
Waterproof layer	-	-
Rockwool	5	0.05
thermal insulators	0.4	0.7

Figure 5 illustrates the amount of ice produced each month of the year, excluding the heat losses from the storage tank walls. As shown, the variation in ice mass across different months is minimal when heat loss is not considered, as the ambient temperature—an important factor influencing heat loss—has not been accounted for. During the summer, ambient air temperatures are significantly higher than in winter, which causes the soil temperature to rise. Consequently, heat losses are greater in the warmer months compared to the colder months.

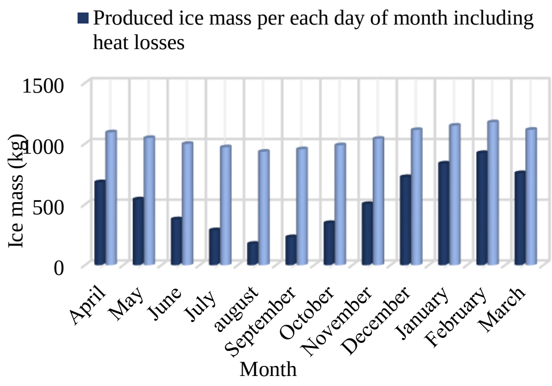

Figure 5. Produced ice mass in month per unit

The heat loss from all six sides of the ice storage compartment was calculated, and the daily ice production was determined, as shown in Figure 5. As indicated, ice production decreases significantly during the warm months. The system performs optimally in the winter, particularly in February, where ice production and efficiency are at their highest. During the coldest six months of the year, the system produces approximately 150 cubic meters of ice, which is highly efficient given the energy consumption.

Based on Figure 5 and considering the precipitation patterns of the Zagros mountainous region, it is optimal to begin ice storage in December. Figure 6 illustrates the total mass of ice accumulated in the storage room over a six-month period. Ice production starts in December and continues through May, as these months provide the highest potential for ice generation compared to other times of the year.

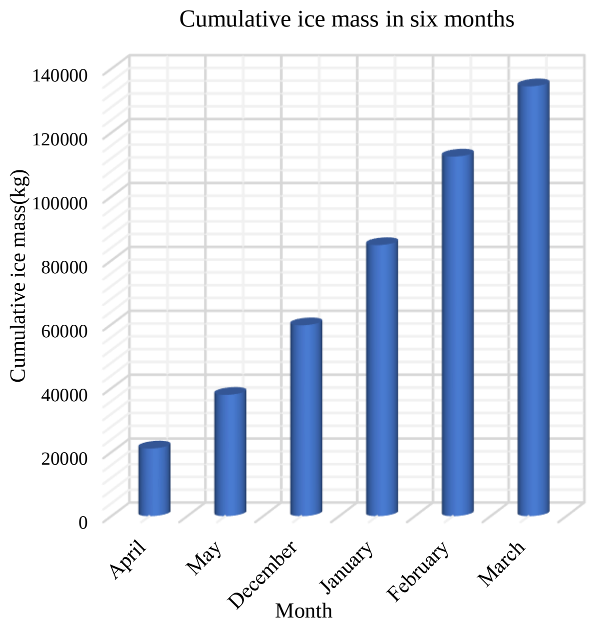

Figure 6. Cumulative ice mass in six months of the year

Under the given conditions, including the refrigeration load and accounting for heat losses from the reservoir and walls, the total mass of ice produced reaches approximately 135,000 kg. This value reflects the outcome of the modeling process, which incorporates losses from the storage tank and reservoir.

To gain a more detailed understanding of ice production over shorter periods, a daily ice mass production chart for February is presented, along with an hourly ice production schedule for February 15th Figure 7 shows the mass of ice produced each day throughout February. On some days, it is observed that when the ambient air temperature rises above 0°C, the refrigeration cycle becomes the sole source of cooling. During these periods, the rate of ice production remains consistent, as it is no longer influenced by ambient air temperature, and the impact of heat loss from the reservoir is minimal. As a result, similar amounts of ice are produced on those days.

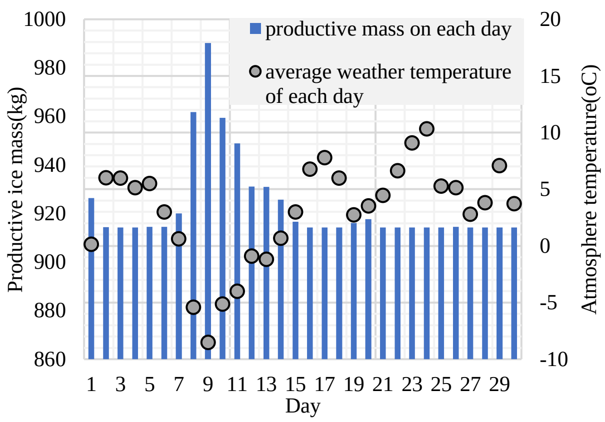

Figure 7. produced ice mass and the average temperature per each day since February

In February, due to the consistently low temperatures, ice production efficiency is at its highest compared to other cold months, with a total output of approximately 27,500 kg. Figure 8 illustrates the ice production on the 15th day of the month, highlighting the increase in production rates as temperatures drop. It is observed that the total mass of ice produced in a single day of February is around 950 kg, equating to a production rate of 0.66 kg per minute. Additionally, the hourly ice production rate for this month is approximately 39 kg.

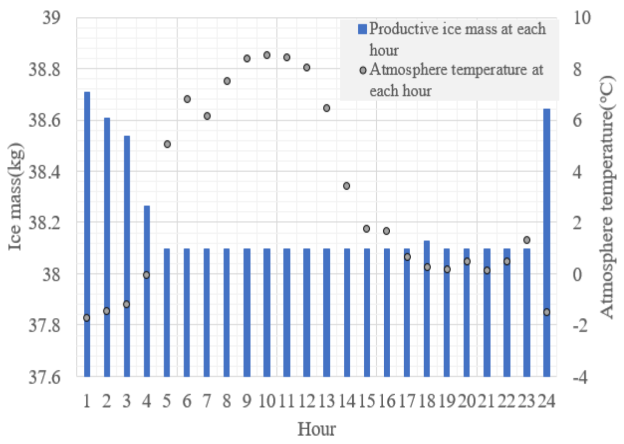

Figure 8. Produced ice mass by air temperature per each hour of day

It is important to note that this level of ice production is directly proportional to the cooling load provided by both the fan and refrigeration cycle. As expected, increasing the capacity of the refrigeration cycle would lead to a corresponding increase in the amount of ice produced.

Figure 9 compares the amount of ice produced over six months since 1986, providing insight into the system's ice production capability for each month. This comparison allows us to assess the fluctuations in ice production over time and better understand the system’s capacity for generating ice under varying conditions throughout the year.

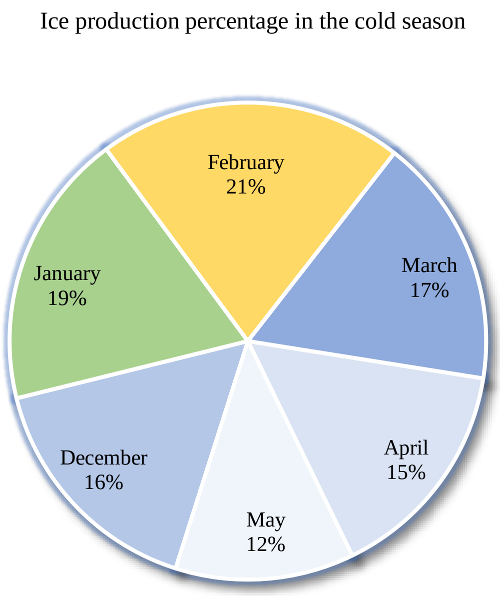

Figure 9. Ice production percentage in the cold season

According to the chart, February accounts for 21% of the total ice production during the cold months of the year, representing the highest production rate compared to other months. This highlights the critical influence of air temperature on ice production. The data from 2017 (1396 in the Persian calendar) further demonstrates that February experienced lower temperatures than other months, explaining its higher efficiency in ice production.

3.2. Economic Analysis

In this section, the economic evaluation of the cold storage system is presented, highlighting its effectiveness in reducing both water and energy consumption, as well as its potential for decontamination. In regions with extremely cold climates, the initial cost of establishing a seasonal cold storage system is typically offset by the energy savings it generates over time. However, in areas where winters are not as cold but summers are exceptionally hot, the primary goal of such projects shifts towards reducing peak energy consumption and balancing the load on the hottest days of the year, rather than immediate cost recovery or profitability.

The analysis compares two cases:

- A house utilising a cold storage system for refrigerant load generation.
- A house cooled by a traditional split cooling system.

Using the Cold Storage System introduced in this study, a 166m³ reservoir with a capacity of 5,000 watts can store approximately 150 m³ of ice at -3°C, which equates to a cryogenic load of 6×10^{10} J. If this system is used to supply refrigeration for three 100 m² homes, as shown in Table 2, it becomes evident that the refrigeration load for these units can be provided for a duration of three months. It is important to note that this system is designed to operate continuously throughout the six coldest months, while the split systems are assumed to run an average of 10 hours per day during the summer.

Table 3 presents the economic calculations for these three 100 m² units under two scenarios: one equipped with a seasonal cold storage system, and the other using split cooling. The comparison reveals that the cold storage system not only reduces energy consumption by 13.73%, but also lowers costs by 22% based on Iran's electricity tariffs. Additionally, the system effectively conserves 150 m³ of water during the high-demand season, transferring it to the warmer months through storage.

As illustrated in Figure 10, the seasonal cold storage system effectively eliminates peak electricity consumption for households during the summer months. Instead, this peak demand is shifted to the winter, when the system stores cold energy for later use.

Table 3. **Comparison and Economic Calculations of 3, 100 m² Apartments with Two Cooling Systems**

	Cryogenic load(w)	Numbers of daily usage for every 3 units	Daily usage hours	Electricity consumption for three units (kwh)	Electricity consumption ratio of three heat pumps to storage system
Three Heat Pumps with Energy Class B	7033.733	90	10	5428.8	1.1
Cold storage system	5000	180	24	6171.4	

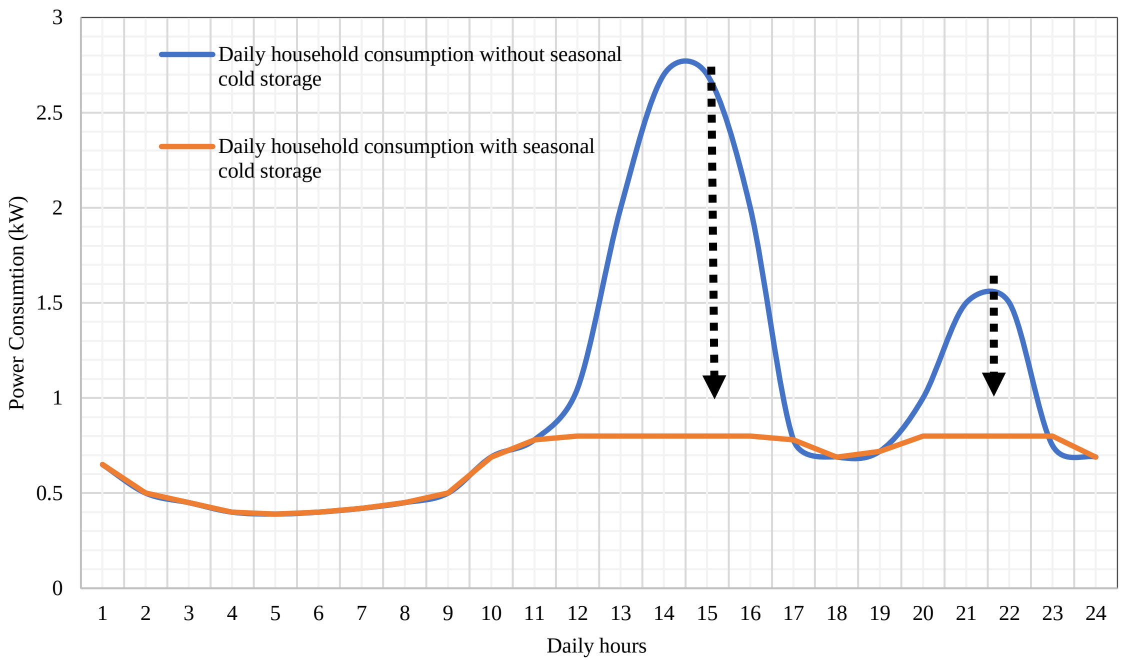

Figure 10. **Electricity consumption decoupling diagram**

4. Conclusion

Seasonal cold storage is a highly efficient and environmentally sustainable method for capturing and storing cold energy during the winter months for later use in the summer. This approach allows cooling energy to be stored in the form of ice, snow, or cold air, reducing energy consumption and shifting demand away from peak periods.

In this study, a computational model was developed to evaluate the performance of a seasonal cold storage system in a dry, mountainous climate. The system utilises both a refrigeration cycle and fan-assisted cooling to generate ice, and the model was applied to assess ice production over a given year. The key findings from this research are as follows:

- The cooling load required to supply cold energy was achieved using two methods. The first method relies on a refrigeration cycle to produce cryogenic energy, which requires electricity consumption. The second method, which uses fan-assisted cooling, is more suitable for colder regions. In this study, both methods were employed to meet the cooling load, demonstrating the system's flexibility and adaptability to different climate conditions.
- Ambient temperature emerged as the most critical factor in ice production. In areas with extremely cold winters, such as high-altitude regions, it is possible to produce ice without consuming additional energy. However, in regions like Tafresh, where winters are not as severe, the use of a refrigeration cycle becomes necessary. Although fan-assisted ice production is not feasible in such climates, it is essential to ensure that the energy consumption for ice production is justified by the benefits it provides.
- The calculations indicated that, by consuming 5,000 watts of energy through the refrigeration cycle and operating the fan at 15 m/s, approximately 150 cubic meters of ice can be produced at a temperature of -3°C. This amount of ice, produced over six months, corresponds to a total cryogenic load of 6×10^{10} J.
- The cold storage system not only reduced energy consumption by 13.73% and costs by 8%, but it also conserved 150 m^3 of water during the rainy season. By storing ice during the cold months, this water was shifted to the warmer season, addressing both energy and water resource management challenges.

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