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Ice Slurry Storage: A Crucial Role in the Consumption of Renewable Energy in Power Grid

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Dear Editor,

In the context of global targets for reaching net-zero carbon dioxide emissions, the energy supply is rapidly shifting toward clean, low-carbon energy systems. Taking the share of renewable energy in 2016 and 2021 as an example, the global electricity generation with renewable energy increased from 7.4% to 12.8%.[1] However, the stochastic and intermittent nature of renewable energy imposes higher requirements on grid flexibility, operational stability, and renewable energy integration. To address these challenges, diverse energy storage systems are being rapidly deployed worldwide on both the supply and demand sides, which contribute a lot to renewable power smoothing, peak load shifting, frequency regulation, reserve capacity provision, and improving operational efficiency.[2]

Among various electricity demands, cooling accounts for nearly 20% of global commercial electricity consumption. Concurrently, global warming is driving a continuous increase in electricity demand for cooling. The rapid increase in cooling load further intensifies grid stress during peak demand periods. The application of distributed energy storage primarily through battery energy storage (BES) and cold storage enables more efficient, low-carbon, and flexible cooling solutions. Although BES systems offer greater dispatch flexibility for power grids, cold storage systems significantly reduce the required capacity of chillers while enabling rapid, large-scale release of cold energy during peak demand periods. Cold storage systems also offer high safety, ease of operation, and simplified maintenance. Moreover, costs for cold storage are substantially lower than BES. Replacing appropriate proportions of BES with cold storage can achieve highly responsive grid dispatch while significantly reducing costs.

There are different kinds of cold storage systems such as water cold storage, phase change material (PCM) cold storage and ice-cold storage. Among all these cold storage systems, ice slurry storage (ISS) system, as a dynamic ice storage technology with high storage density, high coefficient of performance (COP), and decoupling of storage/discharge processes, has attracted significant attention in recent years. Its core medium—ice slurry (a mixture of microscopic ice crystals and liquid water)—possesses excellent fluidity and pumpability. The ISS system offers advantages such as precise cooling capacity control, flexible storage and discharge, and rapid response,[2] enabling more efficient regulation of building cooling load and interaction with the grid.

Figure 1 illustrates the framework of using the ISS system for the consumption of renewable energy in the power grid. During off-peak hours, the system actively produces ice slurry for cold storage. When the grid is under stress or renewable generation is insufficient, the stored cooling energy can be rapidly discharged to offset mechanical cooling load, enabling grid demand response through building cooling load while maintaining end-user thermal comfort.

To advance the large-scale integration of the ISS system into grid demand response, this paper systematically reviews the critical technologies and state-of-the-art advancements in the framework. An analysis evaluates the demand response capability and economic viability of the ISS system by comparing it with the battery energy storage (BES) system and quantitatively calculates the battery capacity that can be replaced by ISS. Major challenges in high-efficiency system design and demand-responsive control for the ISS are analyzed, and potential improvements and key research priorities are proposed.

STATE-OF-THE-ART OF ICE SLURRY ENERGY STORAGE SYSTEM

This section will provide a detailed overview of the technological advancements related to the ISS system, focusing on the ice slurry-making, storage, transportation, and terminal utilization methods of ice slurry.

Ice slurry-making

Ice slurry is a two-phase cooling medium composed of fine ice crystals suspended in water, characterized by excellent fluidity and heat transfer performance. At present, the primary ice slurry-making methods include mechanical surface-scraping, direct contact, vacuum, fluidized bed, and supercooled water,[3] Table in the figure summarizes the fundamental principles, advantages, and disadvantages of these methods.

The process of ice slurry-making with supercooled water mainly involves three key stages. First, the micro ice crystals in the outlet water from the ice tank must be eliminated as much as possible before entering the chiller to reduce the risk of ice blocking during supercooled water generation.[4] Common approaches include filtering to remove fine ice crystals and moderately heating the outlet water to melt crystals, thereby improving the stability of supercooled water generation. Second, in the preparation stage of supercooled water, two main approaches are adopted: indirect heat exchange with the secondary coolant and direct heat exchange with the refrigerant. The former is a mature technology that enables flexible temperature control, but its chiller operates at a lower evaporating temperature and exhibits relatively lower system efficiency. By contrast, the latter allows for a higher evaporating temperature and consequently enhances system efficiency.[5] Finally, the crystallization of the supercooled water must be triggered by external disturbances. Current methods include ultrasonic stimulation, impact collision, and vibration nucleation, among which ultrasonic stimulation is most widely applied owing to its high reliability and low energy consumption.[6]

Despite significant research progress in these key stages, the overall energy efficiency of the method with supercooled water still faces certain challenges. Specifically, heating to melt ice crystals leads to cooling loss, while subsequent cooling for supercooled water generation results in heat–cold offset, both of which restrict the further improvement of system performance.

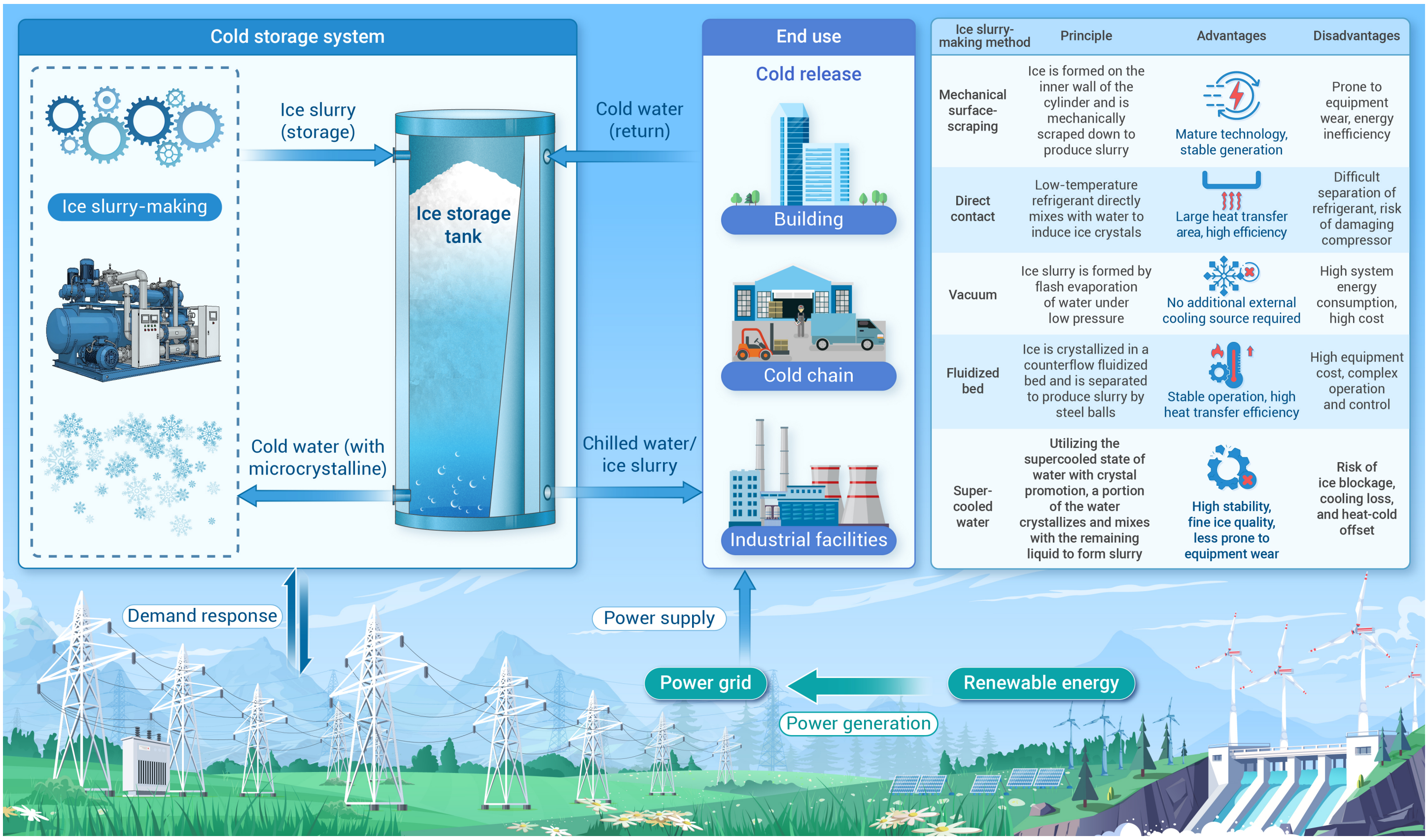

Figure 1. Framework of using ISS system for the consumption of renewable energy in power grid.

Storage and discharge of ice slurry

After production, ice slurry requires temporary (4~48 h) storage in an ice storage tank and subsequent melting to absorb heat from the return water to prepare chilled water for utilization. During ice slurry storage, both the high ice packing factor and high discharging rate should be pursued. Generally, ice slurry storage methods can be categorized into homogeneous storage and heterogeneous storage. Homogeneous storage uses devices such as propellers to agitate the ice slurry within the tank, mitigating phenomena like stratification, agglomeration, and clumping. However, homogeneous storage achieves a relatively lower maximum ice packing fraction (IPF),[7] consumes additional electricity, and ultimately introduces this electrical energy as heat into the storage tank. Heterogeneous storage does not use stirring equipment, making the ice slurry prone to stratification. While heterogeneous storage allows for a higher IPF, it is more susceptible to agglomeration and clumping, making ice slurry extraction more difficult.

For analyzing the change processes of ice slurry during storage, the ice-rich layer model is a widely accepted approach and has been applied in numerous studies. Beyond macroscopic changes, even with a constant IPF, microscopic changes in ice crystals can alter properties such as density and specific heat capacity. Consequently, discrepancies persist between theoretical predictions and experimental results.

During a period of cooling demand, primary heat release methods include direct contact heat exchange, indirect contact heat exchange, and spray heat exchange. Indirect contact heat exchange, where ice slurry transfers heat with a secondary coolant (e.g., chilled water) via a heat exchanger, is commonly used in building air-conditioning systems. However, during ice slurry transport, imbalances in gravity and buoyancy cause stratified flow within pipes at low flow velocities. Ice particles accumulate more densely in the upper section of the pipe, increasing the risk of ice blockage.

Optimal design and operation

The performance of cold storage systems is largely determined by both design and operational control. Their application in building air-conditioning dates back to the 1970s or even earlier, primarily aiming to downsize chillers and ancillary equipment, reduce capital investment, while improving the average load factor of equipment and enhancing energy efficiency. Later, with the advent of time-of-use (TOU) electricity pricing, the design and control objectives of cold storage systems evolved to exploit tariff differentials by strategically shifting cooling loads. Since TOU prices are predetermined and fixed, control strategies typically rely on day-ahead load forecasts to schedule storage and discharging, where simple rule-based approaches are often sufficient to achieve effective optimization.

Currently, with the development of green power grids, the requirements for energy storage systems, including cold storage, are continuously increasing. The design and operational control of cold storage systems must not only target arbitrage under certain TOU prices but also actively respond to long-term power dispatch instructions from the power grid. These conditions necessitate significant adjustments in system design and control, where annual performance optimization and multi-objective optimization control strategies have become indispensable.

The optimal design and control of emerging ISS systems require the following modules: long-term (annual) hourly building load forecasting, short-term accurate load prediction, near-term grid dispatch forecasting, rapid assessment of the power dispatch capacity of cold storage systems, decision-making technology for power dispatch response, and fast predictive control. The challenges they face include: (i) Current design methods focus primarily on building-level peak-valley regulation, lacking capacity optimization frameworks that integrate regional electricity price structures, demand response compensation mechanisms, and market rules; (ii) Existing control strategies are typically designed for TOU demand response, limiting adaptability to the highly dynamic scheduling requirements of modern power markets; and (iii) system modeling remains concentrated on specific building types or regions, with insufficient generalization for diverse climatic zones and load profiles. In addition, comprehensive life-cycle economic and environmental impact assessments are lacking, constraining large-scale deployment of the technology.

APPLICATION POTENTIAL FOR ICE SLURRY STORAGE SYSTEM

To quantitatively evaluate the potential energy storage capacity of the ISS system, a typical office building in Beijing with actual operational data is taken as a case study. By comparing the ISS system with the BES system, the potential for the application of ISS systems in public buildings across China is estimated.

The selected office building in Beijing has a total floor area of 230,000 m^2 and is equipped with a central air-conditioning system. The building's hourly electricity data in 2019 are used for the analysis, covering the electricity consumption for lighting, air conditioning system, chiller plant, and other essential power demands. The building's average daily electricity consumption is 103.2 MWh, with an annual energy consumption of 37,654.5 MWh.

A detailed analysis of the ice slurry energy storage replacement capacity in this case is provided. The results show that although ISS systems provide lower operational flexibility than batteries, their much lower cost enables them to provide a substantial portion of battery dispatchability at a fraction of the cost. At the optimal cold storage rate of 24%, corresponding to an equivalent battery capacity of 8.4 MWh, ISS can deliver about 67% of the dispatchability of BES at only 23% of the cost, demonstrating strong cost-effectiveness. Based on the results, we recommend prioritizing the ISS system for building energy storage applications when the required capacity is below the optimal ratio, as they provide superior cost-effectiveness compared to batteries. For capacities exceeding this threshold, a hybrid approach combining both technologies can maximize both flexibility and economic benefits for the power system. In this case study, the ISS system could replace 8.4 MWh of battery capacity, accounting for 49% of the total required battery capacity (17.1 MWh).

According to the 2021 Annual Development Research Report on China's Building Energy Efficiency,[8] the total area of public buildings in 2019 nationwide reached 13.4 billion square meters, with an annual electricity consumption of 99320 GWh. For the office building case selected, its annual electricity consumption is 37654.5 MWh, requiring a battery capacity of approximately 17.1 MWh. Based on the electricity consumption estimation method, the equivalent energy storage potential of implementing ISS systems in office buildings in China can be derived: the total battery capacity required for the chiller plant in national public buildings is approximately 451 GWh, and the ISS system can replace 49% of the required battery capacity, equivalent to approximately 221 GWh. It should be noted that this extrapolation is a preliminary estimate derived from a single building case study. Regional climate variations, differences in building functions, and variations in cooling system efficiency may lead to significant deviations in the actual nationwide potential.

CHALLENGES IN THE DEVELOPMENT OF ICE SLURRY STORAGE SYSTEM

In order to more effectively utilize the ISS system in promoting renewable energy consumption, the key technical challenges and difficulties associated with the ISS system (taking the supercooled water system as an example), as well as potential approaches for technical improvement are analyzed.

High-efficiency system design based on multiple energy grades

In the buildings, cooling loads can be divided into multiple stages, and thermal sources of different grades have been employed to meet the staged demands, achieving higher system efficiency. Similarly, the processes of cooling, storage and cold release in the ISS system also involve multiple energy grades. However, current ISS system designs often consider only a single cooling demand and a single cooling supply, the utilization of multi-grade cooling sources in the system has not been fully realized. As a result, efficient integration between the ISS system and the air-conditioning system has not been achieved. To overcome this limitation, the energy grades involved in the cooling, storage, and release processes of the ISS system, and the load grades in the air-conditioning system, should be comprehensively analyzed. On this basis, an efficient ISS system process can be constructed according to the principle of supply-demand grade matching.

Under the proposed grade-matching process, cooling loss during the ice-making process can be reduced. In the current ISS, to prevent ice crystal accumulation and blockage in the supercooled water heat exchanger, the outlet water from the ice tank is usually heated to 0.5 ℃ to melt crystals before entering the exchanger for supercooled water generation. This process results in approximately 15%–20% cooling loss, significantly reducing the effective ice-making capacity.[9] Moreover, the remaining ice crystals may cause pipe blockage if melting is insufficient, affecting the stable operation of the system. Through effective grade matching, the issue of ice blockage may be mitigated or eliminated.

In addition, by ensuring a rational grade matching between cooling supply and load demand, heat–cold offset can be avoided. In the ISS system, the heat input during crystal melting is removed later in the supercooled water heat exchanger, forming a typical heat–cold offset process. At present, cooling water is often used as the heat source for melting, but the cooling capacity is not effectively recovered and reused at the terminal side. From the perspective of the entire air conditioning system, the effective cooling capacity is not utilized, thereby limiting the improvement of overall system efficiency.

In summary, by thoroughly analyzing the energy grades in the ISS system and constructing new system processes based on grade matching, issues such as cooling loss and heat–cold offset can be alleviated, and the overall performance of the ISS system in integration with the air-conditioning system can be significantly enhanced.

Challenges in integration into the electricity market demand response

Currently, ISS applications are primarily concentrated in the electricity retail market, with limited penetration into wholesale and ancillary services markets. To enable deeper participation, future research should focus on:

(1) Optimal system design in coordination with electricity markets: Future design should align with diversified electricity market mechanisms by clarifying the role and economic potential of ISS in peak shifting, frequency regulation, and spinning reserve. Multi-objective optimization should determine chiller capacity, storage sizing, and system configuration while considering electricity prices, demand response incentives, thermal inertia, and occupant comfort. This ensures cooling demand is met and market participation benefits are maximized.

(2) Operational control for dynamic market adaptation: ISS operation requires robust modeling and predictive control to address dynamic loads and frequent dispatch across varied buildings, climates, and conditions. By integrating user comfort, grid dispatch signals, and building load dynamics into predictive and real-time control, ISS can enhance adaptability, responsiveness, and flexibility for coordinated participation in both wholesale and ancillary service markets.

From a global perspective, unlocking the potential of the ISS system requires vigorous development of multi-tier electricity markets supported by improved mechanisms and incentive-oriented policies.

CONCLUSION

With the increasing penetration of renewable energy and rising cooling demands, the development of energy-efficient cold storage technologies has become critically important. This paper presents a framework to use ice slurry cold storage system for the consumption of renewable energy in the power grid, and a review of the current research status regarding ice slurry cold storage systems. Furthermore, the energy storage capacity and application potential of ice slurry cold storage systems are estimated based on a comparative case analysis between the ice slurry cold storage system and the battery energy storage system. It is shown that the applications of ISS systems in the public buildings of China have the potential to replace approximately 221,000 MWh battery. To change the potential into reality, low-cost and high-performance technique to control ice crystal growth and agglomeration, and more energy-efficient ice slurry cold storage should be further developed. In addition, a more mature and multi-tier electricity market should be established to encourage further the wide application of ice slurry cold storage systems.

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DECLARATION OF INTERESTS

The authors declare no competing interests.