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Author contributions

Chengchu Yan: Conceptualization, Methodology, Writing - Review & Editing.
Fengling Wang: Writing - Original Draft, Visualization, Formal analysis.
Yan Pan: Resources, Writing - Review & Editing, Supervision, Data Curation.
Kui Shan: Writing - Review & Editing.
Risto Kosonen: Writing - Review & Editing.
A multi-timescale cold storage system within energy flexible buildings for power balance management of smart grids

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Abstract:

Energy storage is widely used in energy flexible buildings, which have great potential for relieving the power imbalance of electrical grids. However, most of the existing energy storage systems are designed for short-term storage, and only a few systems reported for long-term or multi-time scale storage. This paper introduces a new type of multi-timescale cold storage system consisted of a heat pipe-based natural ice storage subsystem and a dual-operation chiller for buildings to enhance their energy flexibility. The proposed system operated in different modes to provide the seasonal cold storage, nighttime chilled water storage, and urgent demand response services, which can be used for relieving the power imbalance in the timescale of the long-term, short-term and real-time respectively. The working principle, system configuration, operation modes, and the implementation of the proposed system for multi-timescale power management, are presented. A case study has been conducted in a building in Beijing to demonstrate the application and effectiveness. Results show that building load factors are greatly improved seasonally (from 19.5% to 49.5%) and daily (from 55.7% to 72.2%), and the power consumption is also considerably decreased (41.2 %) during the demand response (DR) event.

Keywords: energy flexible building; demand response; seasonal cold storage; multi-time scale; smart grid; power balance
Nomenclature:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{load}$</td>
<td>load factor</td>
</tr>
<tr>
<td>$P_{avg}$</td>
<td>average electrical load [kWh]</td>
</tr>
<tr>
<td>$P_{peak}$</td>
<td>peak electrical load [kWh]</td>
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</tbody>
</table>

Subscripts

<table>
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<tr>
<th>Subscript</th>
<th>Description</th>
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<tr>
<td>load</td>
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<tr>
<td>avg</td>
<td>average</td>
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<td>peak</td>
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</tbody>
</table>

1. Introduction

Economic growth and modern society development require a reliable and affordable electricity supply. A power grid must maintain the balance between supply and demand sides at different timescales, i.e., long-term (yearly), medium-term (monthly), short-term (daily or hourly), and real-time (minutes or seconds) [1]. Otherwise, it will cause a series of problems, such as low efficiency, high pollutant emission, energy waste, voltage sags, and facilities damages. The high penetration of renewable generations (e.g., photovoltaic power stations, wind farms) brings significant challenges for the power grid due to their intrinsic randomness and variability. There usually are two conventional approaches for relieving the power imbalance and peak load: (1) to build standby power plants; (2) to employ energy storage devices/systems (e.g., batteries and pumped-storage power stations) [2]. Nevertheless, the high initial and operation costs impeded the first approach’s application, and the cost-intensive, low storage capacities and geographic limitation prevented the second one. By contrast, altering the power demand through demand side-management (DSM) and demand response (DR) on the demand side of the grid is considered as a more effective and promising solution for relieving the power imbalance since it uses no fuel, produces no residual environmental impacts and caused no wear and tear on generation, transmission and distribution equipment. The end-users on the power demand side can help the electrical grid shift their peak loads from peak periods to off-peak periods and treat their demands as “operating reserves” in a more cost-effective manner, particularly when thermal storage are extensively employed [3].
Buildings, as one of the essential electricity consumers worldwide, consume about 74% of the total electricity in the US [4] and over 91% in Hong Kong [5], are likely to play an essential role in assisting the grid to deal with the imbalance issues at different time scales. Energy efficiency improvement, peak load management, and demand response (DR) are three typical demand-side management approaches for long-term, medium-term, and short-time, respectively [6]. Enhancing energy efficiency can reduce the peak load by minimizing the overall energy consumption and maintaining services level, which can provide a constant load reduction and a long-term benefit for power generation planning. Typical peak load management methods, including demand limiting and demand shifting, are generally motivated by higher charges for peak demand or time-of-use (TOU) rates. For instance, thermal storage systems used to shift the heating/cooling loads from the peak periods to the off-peak periods can consequently alter the power demand profiles [7]. DR refers to the modification of building electricity usage within a short-term period for addressing the system reliability and dynamic peak load reduction from the grid [8].

To emphasize the importance of building energy flexibility on energy networks, the International Energy Agency (IEA) introduced ‘Energy Flexible Buildings’ with the project ‘Annex 67’. According to the interpretation, energy flexible buildings should have the capacity to manage their energy demand and production according to local climate conditions, user needs, and grid requirements [9]. Although the concept of ‘Energy Flexible Buildings’ is relatively new, similar concepts or topics can be found in recent studies. For instance, Wang proposed ‘grid-friendly and grid-responsive’ buildings and considered that being friendly and responsive to the smart grid should be an essential and advanced feature for modern buildings [10]. Hence, energy flexible buildings are specifically required to work in synergy with (i.e., being responsive) the grid, or avoid additional stresses (i.e., being friendly) on the power grid balance. Lizana et al. presented a flexible energy building concept based on smart demand-side management and high-density latent heat storage [11]. Aduda et al. summarized some critical building performance implications when using buildings as demand-side flexibility resources to provide flexible services to the grid [12]. Junker et al. proposed an indicator named ‘flexibility function’ to measure the response of a building to a penalty signal from the grid, which is used to characterize the energy flexibility of buildings and districts [13]. Reynders et al. summarized the definition and quantification methods for energy flexibility, mainly focused on thermal storage in energy flexible buildings [14]. Vigna et al. viewed both the theoretical approaches and available indicators to evaluate the energy
flexibility of building clusters [15]. The researchers and industry experts of Alliance to Save Energy also agreed that ‘the evolution of a fully integrated Building-Grid ecosystem can greatly optimize system efficiencies, reliability, and cost-effectiveness at both the building and grid-scale’ [16]. The literature shows that energy flexibility has been widely recognized as a critical resource for future buildings and energy systems.

Among existing technologies for building energy flexibility enhancement, active thermal storage is considered a promising solution and has attracted more researchers. Compared with the passive storage (i.e., building thermal mass [17]), the active thermal storage generally can provide much more thermal capacity and better controllability of power alternation with less negative impacts on the building occupants’ comfort [18]. Yan et al. proposed a flexible demand control system combined with a large-temperature difference chilled water storage to provide short-term and real-time load shifting ability for the power balance of the grid [19]. Wang [10] summarized three typical categories of building active storage applied for the energy flexibility enhancement, which includes conventional storage (e.g., chilled water storage), small-scale storage (e.g., phase-change material), and innovative use of existing building facilities (e.g., fire water tanks) for load shifting, demand limitation, and management. From the storage duration aspects, the conventional chilled water (or ice) storage is a typical short-term storage system usually providing the daily cold (or heating) storage, while the long-term storage indicates the storage duration beyond at least one cold and one hot season, which usually is up to several months. Arteconi et al. evaluated the effectiveness of a heat pump coupled with a TES system for a DSM strategy. The results showed that it could shift the on-peak demand to off-peak times and flatten the shape of the electricity load curve. They used water as the cold storage medium, which resulted in larger storage volume and can only provide short-term services [20]. Jesus Lizana also proposed a novel demand-side management to predict the best operational strategy according to various conditions. The results showed about 20% of the end-users’ electricity bill savings [21]. Although the combination of chillers and TES can enable the flexibility of electricity usage, most of the research works focus on the short-term flexibility performance [22]. Long-term storage is somehow called seasonal thermal energy storage (STES). Moreover, the STES can be identified as seasonal heat storage and cold storage. The first type stores heat from a solar thermal harvesting system during hot months into a storage tank (usually installed underground), and extracts for heating during cold seasons, and the second type stores cold (e.g., snow, ice) in winter and extracts for the air-conditioning purpose in summer [23-26]. It
is noteworthy that most of the existing studies on long-term storage aim to improve the cost-
effectiveness, environmental sustainability, reliability, and stability of the energy system,
instead of improving the power imbalance of the grid [27].

In summary, since the importance of energy flexibility for the power balance of the grid has
been widely recognized, more and more researchers have considered the active thermal
storage as a promising solution to enhance the building energy flexibility. However, when the
energy storage systems applied for the power balance regulation of the gird, most of the
current systems are designed for a short-term scale, and only limited systems are reported for
long-term grid balance regulation, not to mention the systems that can be used for multi-
timescale power balance of grids. Besides, the current building energy systems mainly aim to
improve the building energy efficiency or reduce the operating cost, rather than to improve
the energy flexibility from the perspective of the grid balance. Such limitations seriously
reduce the capacity of building energy flexibility and greatly hinder the building’s potential to
improve the reliability and security of the power grid. To meet the increasing requirements
for relieving the peak load and the power imbalance of smart grids, more effective and multi-
time scale energy storage systems should be developed for modern buildings.

This paper introduces a new type of a multi-time scale cold storage system for an energy
flexible building. The proposed system can operate in five different modes to provide the
seasonal cold storage, nighttime chilled water storage, and urgent demand response services,
which can be used for relieving the power imbalance in the timescale of the long-term, short-
term, and real-time respectively. There is a lack of research about building energy storage
systems from the view of the grid balance at multiple time scales. The novelty and
collection of this paper presented as below: (1) proposing a compact cold storage system
that can integrate different timescales; (2) enabling an energy flexible building to provide
long-term, short-term, and real-time power management services for smart grids; and (3)
validating the effectiveness of energy flexible buildings to the grid power balance at multiple
time scales through a case study. The following structure in this paper is: Section 2
introduces the working principle, system configuration, and operation modes of the proposed
 compact cold system. Section 3 describes the implementation of the proposed system for a
multi-time scale power balance and discuss and analyze the results based on a case study.
Finally, Section 4 summarizes the main findings of this research and the future work.
2. Methodology

2.1 A compact multi-timescale cold storage system within buildings

Most existing long-term storage systems are designed for large energy systems, such as district heating and cooling systems. The lack of long-term storage systems for single or small-sized buildings is because with the decreasing of the storage size, the energy-efficiency will decrease, and the specific construction cost will increase [28]. This paper proposes a multiple timescale cold storage system for a small-sized building. Combined with a seasonal ice storage system and a mechanical cooling system, this system can provide the cold storage across different timescales. It can be seen that the seasonal ice storage system can provide long-term storage and the mechanical cooling system short-term. The control strategies and operating modes will be explained in section 2.3 operation modes. This novel configuration is inspired by the complementarity between the seasonal cold storage and mechanical chiller.

For seasonal cold storage, it is sustainable cooling technology while it suffers from certain limitations: (1) relative large space requirement for the ice or snow storage [29]; (2) poor reliability and controllability on the cooling supply due to its high weather-dependent, and (3) significant cold loss (i.e., 40–60%) during the long-term storage [30]. By contrast, the mechanical chiller has better reliability and controllability on the cooling supply and the short-term (mostly daily or really-time) cold storage, which requests less storage space and results in a less cold loss. In conclusion, the proposed multiple timescale cold storage system can integrate the advantages of both long-term cold storage and diurnal chilled water storage (provided by the mechanical chillers).

2.2 System configuration

As illustrated in Fig. 1, the system consists of a heat pipe-based seasonal cold storage system and a dual-operation chiller for providing long-term and short-term cold storage, respectively. The water/ice storage tank usually is installed underground with good insulation and waterproof to avoid cold loss and water leakage, especially for long-term storage. This proposed system has been validated in our previous studies [23, 31]. Different from the previous studies, they are mainly addressed evaluating the feasibility and optimizing the cost-effectiveness of using the seasonal cold storage technology. This paper focuses on improving the energy flexibility of buildings from the perspective of the grid balance enhancement. Using and modifying the proposed system as a multi-time scale cold storage system enables buildings to provide long-term, short-term, and real-time power management services for smart grids in an integrated approach.
This system consists of a separate-type of heat pipes, which can provide long-term storage. The heat pipes are made of high thermal conductivity material and vertically installed [32]. The evaporator segments are immersed into the well-insulated water tank while the condenser segments are exposed in the ambient. In the cold season (winter), when the ambient temperature is lower than the tank’s water temperature, the refrigerant sealed inside the heat pipes at evaporator segments starts to extract energy from water and be vaporized. The vapor then reaches the condenser segments along the ascending pipe and rejects the heat to the low-temperature ambient. After releasing the latent heat to the ambient, the refrigerant condenses to liquid and goes back to the evaporator segments due to gravity. By repeating this refrigerant cycle, the heat exchange happens, and the water inside the underground tank is freezing. In early summer, by circulating the chilled water into the underground tank, the stored natural cold can be extracted to provide the free cooling through the air-conditioning terminals. After all the stored ice melted, the water is used as a cold storage medium for short-term cold storage, i.e., diurnal chilled water storage. The chilled water is produced by the dual-operation chiller when it operates in the chilled water storage mode. Another mode of this chiller is the air-conditioning mode.

Further to increase the operating flexibility, an outer-inner zone configuration is applied. The

Fig.1 Schematic of the multi-timescale cold storage system
cold storage tank is divided into two zones by a conductive partition wall with a switchable window (as shown in Fig.2). Most of the time, the switchable window is closed to separate the two zones physically. The outer zone is functioned as a normal seasonal cold storage tank. Usually, only the ice in this part would be used for free cooling in the early summer. When it melted utterly, this zone then is used to store the chilled water. The ice in the inner-zone is only used in some critical or urgent moments. For example, to discharge a large amount of cold in a very short time scale (e.g., 15~30mins) when the electricity supply of the grid is in shortage, the operator can open the switchable window to utilize the inner zone ice. Compared with no-zoning tank configuration, the outer-inner zone configuration can significantly enhance energy flexibility without any appreciable impact on the original system performance.

Fig.2 The outer-inner zone configuration of cold storage tank

2.3 Operation modes

After the cold storage tank (with both outer/inner zones) has been fully charged with the ice through heat pipes automatically during the cold season, five operation mode, including normal cooling mode, outer zone ice discharging mode, chilled water discharging mode, chilled water charging mode, and inner zone ice discharging mode would be identified respectively. The red line circuit illustrated in Fig. 3 is the normal cooling mode, and this is the traditional cooling operation mode where the chiller produces the 7/12°C chilled water to satisfy the space cooling via air-conditioning terminals. The other four operation modes, listed in table 1, can be realized by switching corresponding pumps and valves. Generally, the
outer zone ice discharging mode starts at the beginning of the cooling season. Under this mode, circulated chilled water extracts cold from the outer zone ice for the whole building as free cooling. When the outer zone ice melted completely, i.e., the pre-stored cold is consumed completely, the chilled water will be utilized as the medium for the short-term cold storage application. The dual-operation chiller produces the chilled water at 4/9°C to charge the outer zone during the nighttime, and discharge to accommodate part of the daytime cooling load or the whole load. These charge and discharge processes are named chilled water charging mode and chilled water discharge mode. If the chilled water from the storage tank cannot provide the whole building’s cooling during the daytime, the normal operation mode will operate as supplementary. The inner zone ice discharging mode only operates under critical situations, such as to discharge a large amount of cold in a very short time scale when the electricity supply of the grid is in shortage. Under this mode, the chiller will be shut down immediately, and the switchable window will be open. The return chilled water (12°C) flows into the inner zone and mixes with ice or ice-water mixture directly to discharge the cold so that the cooling demand gap will be filled by the cold released from the inner zone very quickly.

Fig.3 Schematic to realize different operation modes

Table 1 Setting combinations of the five cold storage system operation modes
3. Results and discussion

3.1 Application for multi-timescale power management

Energy flexible buildings are designed to be ‘grid-friendly’ and responsive to the requests or ever-changing conditions of the power grid. Buildings can provide three types of power management strategies with different time scales by applying the proposed multi-time scale cold storage system. They are seasonal energy management for the long-term, day-ahead power management for the short-term, and power demand response for the real-time (i.e., hour-ahead/15 minutes-ahead) power balance, respectively.

3.1.1 Seasonal energy management

Wang et al. have defined load factor as the average load over the peak load in a specific period (i.e., one year or one day) to represent the ratio of the average load and peak load [1]. From the definition, a high load factor indicates a flat or a constant cooling load or power demand profile, which is preferred by grids because this factor indicates low grid capacity demand and stable supply requirement. In other words, this is a grid-friendly load profile so that the load factor can be used to indicate the level of grid-friendliness [10]. As shown in Eq. (1), where $f_{load}$ is the load factor, $P_{avg}$ is the average electrical load of a grid during the given period, and $P_{peak}$ is the peak electrical load of the grid during the same period.

$$ f_{load} = \frac{P_{avg}}{P_{peak}} \quad (1) $$

On most occasions, the high demand air-conditioning operation time overlaps with the peak-hour for the grid, which greatly exacerbates the seasonal power imbalance between supply
and demand sides. For most commercial or office buildings, chillers are usually the largest electricity consumers whose power consumption can approximate proportional to the cooling load. Based on this fact, the cooling load profile of chillers can reflect the power demand profile of a building according to some researches. In this study, although the load factor is defined to evaluate the grid electrical power profile, it is also used for quantitative evaluation of the cooling load profiles of a building.

Fig. 4 illustrates the comparison between applying/not applying the seasonal power management on the power profile improvement. It clearly shows the yearly load factor increase. By facilitating the proposed compact cold storage system, quite an amount of cold is charged during the winter and stored in the tank for several months without consuming any electricity, and then can be used for space cooling in summer. As a result, the electricity consumption for cooling can be greatly reduced in the summer, particularly in the hottest months (e.g., July or August) when the yearly peak demand occurs. The load factor can also reflect the influence since it is determined by the ratio between the average and the peak electricity load. The flatten curve indicates a better load profile, and Fig. 4 shows the trend. The shadow represents the accumulated power reduction because of the use of seasonal ice storage, which is determined by the stored quantity and cold consumption in different months. In this study, the outer zone will be first discharged in the early summer and used as the chilled water storage tank after the stored ice melted completely. At the same time, the cold in the inner zone will be gradually released throughout the whole cooling season, or at least until the yearly peak demand period during the hottest months when the inner zone size is sufficient.
Fig. 4 Monthly building power demand profiles with/without seasonal cold storage

3.1.2 Day-ahead power management

The common strategies for day-ahead power management, such as load shifting and peak load shaving, are usually combined with economic incentives by time-of-use (TOU) pricing or dynamic pricing [33]. Generally, much lower electricity prices in off-peak hours can encourage the building owners to alter their energy consumption behaviors to reduce the operation cost.

Fig. 5 illustrates the hourly power profile to be altered under the day-ahead power management and results in the daily load factor increasing of a building. In a typical cooling day of summer, the dual-operation chillers operate the ‘chilled water charging mode’ in nighttime and ‘normal cooling mode’ in the daytime if the stored chilled water cannot accommodate the whole building cooling load. By doing this, a large proportion of daytime building cooling load will be shifted to the off-peak period, consequently, flatten the cooling load profile curve.
3.1.3 Power demand response

Power demand response (DR) is designed to solve short-term and real-time power imbalance issues from the power demand side by reducing the electricity consumption at peak load time or when system reliability is threatened [24, 35]. According to the urgency of DR request, DR measures can be categorized as offline power DR (e.g., day-ahead power management) and online power DR (e.g., hour-ahead/15 minutes-ahead). The offline power DR usually is diurnally scheduled to increase the load factor (as described in section 3.2), while the online power DR is used to enhance the grid reliability and quality by treating the power demands as the ‘transient’ operation events and serving for emergency cases.

Direct Load Control Program (DLCP) and Emergency Demand Response Program (EDRP) are the most typically applied online DR measures, both of which can be realized by immediately shutting down the operating chillers without or with a little bit influence on the indoor thermal comfort in the response of the electricity reduction requirement from the grid [36]. The difference is that for the DLCP, the chillers will be switched off by the utility company directly when necessary, and a guaranteed payment usually will be offered to the users as compensation based on the previous agreement. For the EDRP, the users can choose or reject the switch-off notification and the compensation payment.

In this study, when the power shortage on the grid is predicted, a switch-off notification will
be delivered, and then the chiller will be shut down for a while (e.g., 15mins/30mins or even longer) no matter applying DLCP or EDRP. During this period, the chilled water storage tank will provide the total building cooling requirement. In case the chilled water discharge rate of the outer zone is not sufficient, the switchable window should be open so that the ice/water in the outer/inner zones will be mixed physically to increasing the discharge rate.

3.2 Case study

A case study is conducted in a small-sized building in Beijing to evaluate the performance of the proposed compact cold storage system on improving the power balance during different timescales. Beijing is a city located in North China, which is deeply influenced by the continental monsoon climate. The cold, windy, and arid winters can ensure an excellent charge performance of the heat pipe-based seasonal storage system.

3.2.1 Building and system description

The concerned building with a total gross area of 2000 m$^2$, implemented various renewable energy technologies and control strategies, including solar energy, underground thermal energy as well as this proposed cold storage system, aims to become a low-energy building [31]. The operating hours of this building are from 7:00 am to 9:00 pm and avoid the off-peak power period in Beijing (from 11:00 pm to 7:00 am the next morning), making it a perfect object to apply the short-term thermal storage strategy [37]. Recognized as one of the best building energy simulation tools, DeST has been applied to simulate the building cooling load and energy consumption data [38]. Fig.6 presents the hourly building cooling load during the cooling season. From this figure, the cooling season for this building is from April to November. The total building cooling demand is approximately 83,100 kWh during the whole cooling season. The peak cooling load happens on the 2nd August, and the total daily cooling demand is about 1060 kWh, hence considering the design day is the 2nd August, and the design cooling capacity is 1060 kWh. Three stages, named as the early summer stage (from the beginning of the cooling season till around the 15th May), pre-peak summer (the 15th May to the 2nd August) and post-peak summer (after the 2nd August till the end of the cooling season) are designated over the cooling season, and different operation strategy is applied for each stage.

This concerned building is equipped with a storage tank of 450 m$^3$ volume (the outer zone volume is 165 m$^3$ and the inner zone 285 m$^3$) and a dual-operational chiller with 38 kW cooling capacity (46% of the design cooling capacity). In our previous studies, we studied
the method to determine the seasonal cold storage system volume and chiller capacity [23, 31]. The storage tank can provide about 28,350 kWh effective cold during the cooling season after being fully charged by the end of March (i.e., just before the cooling season starts). The ice in the outer zone can provide sufficient cold energy to accommodate the free cooling demand of the whole building during the early summer and then be used to store all the chilled water produced by chiller during the nighttime. The inner zone ice melts gradually to discharge cold energy through the conductive partition wall without physical mixture and also can discharge quickly by opening the switchable window in urgent cases. In most operation years, the inner cold energy can be maintained until the post-peak summer stage to reduce the building’s peak electricity demand.

![Hourly building cooling load profile in a cooling season](image)

**Fig.6 Hourly building cooling load profile in a cooling season**

**Table 2: Specification of the multi-timescale cold storage system**

<table>
<thead>
<tr>
<th>Material and thickness:</th>
<th>Surface area:</th>
<th>Refrigerant:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat pipe</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stainless steel pipe</td>
<td>Evaporator 375 m$^2$</td>
<td>R22</td>
</tr>
<tr>
<td>$\Phi_0=25$mm</td>
<td>Condenser 750 m$^2$</td>
<td></td>
</tr>
<tr>
<td>Chiller and storage tank</td>
<td>Chiller cooling capacity:</td>
<td>Outer tank volume:</td>
</tr>
<tr>
<td>38 kW</td>
<td>165m$^3$</td>
<td>285 m$^3$</td>
</tr>
</tbody>
</table>
### 3.3.2 The performance of multi-timescale power balance

**Seasonal cooling shifting and shaving**

The proposed cold storage system can form a flattened, reasonable seasonal cooling load profile that plays a vital role in improving the grid’s long-term power imbalance. As discussed above, the power consumption of the chiller can indicate the power demand profile of a building because the chiller power consumption is approximately proportional to its cooling loads. Fig.6 shows the original building cooling load profile. The 19.5% of the calculated load factor reveals the building electricity load factor might be close to 19.5% when applying a conventional air-conditioning system (i.e., without any storage and the total building cooling is provided by chillers). After using the proposed compact cold storage system, only part of the constant building cooling load has to be handled by the chiller, and the rest of the cooling load will be dealt with by cold storage systems. As shown in Fig.7, the chillers even do not need to operate in the early summer since the outer zone ice accommodates all the cooling loads. In the hot summer, the system operates in chilled water charging mode in the nighttime, the normal cooling mode, or the chilled water discharge mode in the daytime. During the nighttime, the chiller usually works at full load or high load conditions, which results in a constant chiller cooling load profile and a relatively significant cooling load factor as 49.5%. 

<table>
<thead>
<tr>
<th>Material and thickness:</th>
<th>Overall heat-transfer coefficient</th>
<th>Cold loss rate:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank insulation</td>
<td>0.3 W/m²·°C</td>
<td>&lt;10%</td>
</tr>
<tr>
<td>Zoning partition</td>
<td>6.0 W/(m²·K)</td>
<td></td>
</tr>
<tr>
<td>wall/window</td>
<td>Switchable window area: 2 m²</td>
<td></td>
</tr>
</tbody>
</table>
Day-ahead cooling and power management

We evaluated the performance and effectiveness of the proposed system for short-term (day-ahead) power balance management on the design day. The cooling load distribution profile is shown in Fig. 8, the black bars indicate the original cooling load during the operational hours (i.e., 7:00 am to 9:00 pm), and the green and blue bars the shifted cooling by applying the storage proposed system. The hourly cooling load of the chiller equals the hourly building cooling load when using a conventional air-conditioning system. In this case, the peak building cooling load is 83 kW, and the daily average cooling load is 46 kW, which results in 55.9% of the cooling load factor. When using the proposed system, a part of the building cooling load is shifted and accommodated by the ice of the seasonal cold storage system (both inner/outer zones) and the dual-operation chiller during the night. The dual-operation chiller operates in the normal cooling mode during the daytime and in the chilled water charging mode during the nighttime off-peak period. Due to the cooling load distribution among different systems and different periods, the chiller’s cooling load profile flattened. The daily average and maximum chiller cooling load are 35 kW and 38 kW, respectively, which results in the building cooling load factor as 92.5%.
As the most prominent power consumption equipment in a building, a chiller can effectively provide cooling shifting and shaving capacity by turning it on and off. Fig. 9 shows the comparison of the building power demand between using a conventional air-conditioning (AC) system and the proposed system. In this study, the building power demand is the sum of the chiller power, other AC auxiliary components (e.g., pumps, fans, cooling towers), and all the other non-AC consumers (e.g., lighting, office devices, appliances). Although the power demand of non-AC consumers does not change during this process, the power demand of chiller and its associated auxiliary components are decreased due to the cooling load shifting by chiller shut down. The power load factor of the building is consequently increased from 55.7% to 72.2%.

Fig. 8 Cooling load distribution profile on the design day (2nd August)
Demand Response performance

Besides the day-ahead load shifting, the cold storage system can also enable the real-time demand response strategies for the building. When a grid reliability-triggered event encountered, a considerable power demand reduction would be achieved immediately by shut down the chiller, and the energy storage tank will provide the alternative cooling grateful the high flexibility of the cold supply. Fig.10 shows the power alteration potential of the building for a real-time emergency demand case. The maximum power demand line represents the building power demand when using the day-ahead chilled water storage, and the minimal power demand including the non-AC loads and others from the AC auxiliaries (e.g., pumps and fans) when shut down the chiller. During this period, the total building cooling load is accommodated by the stored chilled water, where the low temperature chilled water from the inner zone is mixed with that of in the outer zone via the open switchable window. The average maximum power demand line of the building is 19.8 kW during the occupancy period, while the average minimal power demand line is 11.6 kW, which indicates the potential flexibility of this building in response to the grid power reduction is about 41.2%. 

Fig.9 Hourly building power demand profile on the design day
3.3 Discussion of application issues

Although many researchers have recognized the significance and high value of energy flexible buildings for future energy systems [9-14], most of the studies are limited in a specific time scale, especially for short periods. The proposed system combines the function of seasonal ice storage and diurnal thermal storage (provided by one cold storage tank) and integrates a dual-operation chiller. It can reduce the excess capacities of power plants and the extra operating reserves (e.g., a spinning reserve of generators) in the power generation side, resulting in significant initial capital and operational cost saving [18]. In the power balance management circumstance, buildings usually participate a specific electricity tariff scheme (e.g., time of use pricing, critical peak pricing, demand bidding), thus achieving cost savings.

Economic performance is another essential factor that affects the application of the proposed cold storage system in practice. The proposed system is a heat pipe-based seasonal cold storage system combined with a dual-operation chiller. The initial cost includes purchasing and installing the separated heat-pipes, chiller, associated auxiliary equipment, and the land and construction cost of a storage tank. Based on a rough estimate, the proposed system’s initial cost is about 2.5 times that of a conventional cooling system (i.e., cooling by an electricity-driven chiller). The savings from the operating can compensate for the increased initial cost from three aspects:

Fig. 10 The potential reduction of power demand for Demand Response
The stored ice providing free cooling in early summer can reduce the chiller operation cost. It provides about 34% of the total cooling demand in this case study.

Shifting the cooling load from high-priced peak hours to low-priced off-peak hours (e.g., 1/4~1/3 of the price in peak hours) can save the electricity tariff.

The incentive benefit by providing real-time DR to the grid. It is considerable but challenging to quantify because it strongly depends on the pre-contracted payment rates and the DR events’ duration and frequency.

Based on annual energy and cost analysis by DeST, the operating saving from the first two aspects is about 76% compared with the conventional cooling system. The estimated payback time of the proposed cold storage system is about 8~10 years. A more detailed investigation of cost-effectiveness is necessary for future studies.

Climate restriction and electricity incentive policy are the two significant limitations for the practical application of the proposed system. The proposed cold storage system can only be effective when applied in the cold winter climate zone to ensure the charging performance of the seasonal ice storage. Usually, the average outdoor temperature in winter should be lower than 0°C [29]. Besides, most existing electricity incentive programs are designed exclusively for industrial or large commercial consumers [39]. The small-sized or residential buildings may not be allowed to participate in power demand management schemes. Without the benefits of electricity incentives, the proposed system cannot fully reflect the advantages of operating cost savings.

4. Conclusions and future work
This paper introduces a new type of multi-timescale cold storage system consisted of a heat pipe-based natural ice storage subsystem and a dual-operation chiller for buildings to enhance their energy flexibility. Three cooling and power management strategies, including seasonal energy management, day-ahead power management, and power demand response, have been applied to achieve long-term, short-term, and real-time power management, respectively. These power managements can reduce the excess capacities and the extra operating reserves in the power generation side, resulting in significant economic and environmental benefits. A case study is conducted in a small-sized building in Beijing to evaluate the performance and effectiveness of the proposed system on energy flexibility enhancement. The main findings of the research work are summarized as follows.
• Cold storage system combined with heat pipes and chilled water shows great complementary on the performance and configuration. This kind of system integrates the advantages of both the natural cold storage and the mechanical cooling system.

• Better than a single tank storage configuration, an outer-inner zone configuration can provide more operating flexibility. In this study, five typical operation modes have been identified, and more flexible arrangement of cooling and power usage in the building would be realized.

• Three types of power management strategies can be effectively implemented for facilitating the power balance of the smart grid at different time scales. According to the results from case study, (1) the seasonal building cooling load factor increases from 19.5% to 49.5% demonstrating the long-term management effectiveness. (2) the building power load factor increased from 55.7% to 72.2% demonstrating the short-term power balance improvement; (3) an immediate power reduction by 41.2 % in response to the real-time DR during the peak cooling period on the design day.

• The savings from the operating can compensate for the increased initial cost from three aspects. They are free cooling from stored ice, electricity tariff reduced by loading time shift, and incentive benefit by providing real-time DR. A more detailed investigation of cost-effectiveness is necessary for future studies.

• The payback time of the proposed system is about 8~10 years in the case study. Climatic restriction and electricity incentive policy are two significant limitations for the practical application.

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**Highlights:**

- A cross-timescale cold storage system is proposed for energy flexible buildings.
- Three energy management strategies applied for energy flexibility enhancement.
- The system can be used to relieve the power imbalance in different timescales.
- Load factor improved from 19.5% to 49.5% seasonally and from 55.7% to 72.2% daily.
- The power consumption is considerably decreased (41.2 %) during the DR event.
Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: