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Optimal Design of Active Cool Thermal Energy Storage Concerning Life-cycle Cost Saving for Demand Management in Non-residential Building

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Abstract

This research provides a method in comprehensive evaluation of cost-saving potential of active cool thermal energy storage (CTES) integrated with HVAC system for demand management in non-residential building. The active storage is beneficial to building demand management by shifting peak demand as well as providing longer duration and larger capacity of demand response (DR). In this research, it is assumed that the active CTES is under control of the fast DR strategy during DR events and storage-priority operation mode to shift peak demand during the normal days. The capacity of active CTES is optimized under the incentives of both modes.

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Keywords: Active cool thermal energy storage; Building demand management; Demand management; Life-cycle cost saving

1. Introduction

Building sector is one of the major sectors of the energy consumption. According to the 2009 buildings energy data book provided by the U.S. Department of Energy, the buildings sector consumed 74% of U.S. electric energy consumption [1]. In Hong Kong, the energy consumption of buildings occupied 90% of the total electric energy consumption in 2008 [2]. Therefore, proper management of the building energy use will be not only essential for the reliable operation of the whole grid but also beneficial in cost saving for the building owners.

Building demand management has been adopted and it includes two main parts: the peak load management (PLM) and the demand response (DR) [3].

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The former one is usually motivated by high charges for peak demands or time-of-use rates based on the electricity price structure which considers the time and the quantity of electricity used. The later one refers to event-driven and can be defined as short-term modifications in customer end-use electric loads.

Within the building sector, the heating, ventilation and air conditioning (HVAC) systems are the major contributors to the energy consumption of buildings, which even consume 60% of the building energy in hot climate locations [2]. In recent year, cool thermal energy storage (CTES) has been widely used by integration with HVAC system to shift cooling load in buildings**.** It can bring considerable cost saving by reducing peak demand for PLM. Meanwhile, it can also enlarge the demand response capacity by discharging cooling [4]. CTES systems can be further divided into "active" and "passive" systems. "Active" denotes that CTES systems require an additional fluid loop to charge and discharge the storage tank [5]. The passive means that the use of CTES as well as melting and freezing of CTES medium are realized without resort to mechanical equipment [6].

This study aims to provide a guidance in comprehensive evaluation of cost-saving potential of CTES integrated with HVAC system for building demand management, including both PLM and fast DR. During the DR event, income from fast DR can be achieved through activation of the active CTES. During the normal days, the active CTES can be also used to shift peak load for reducing the high charge of peak demand. The law of marginal decision rule is used to optimize the capacity of active CTES and to determine the corresponding life-cycle cost saving potentials.

2. Research flowchart and optimization method introduction

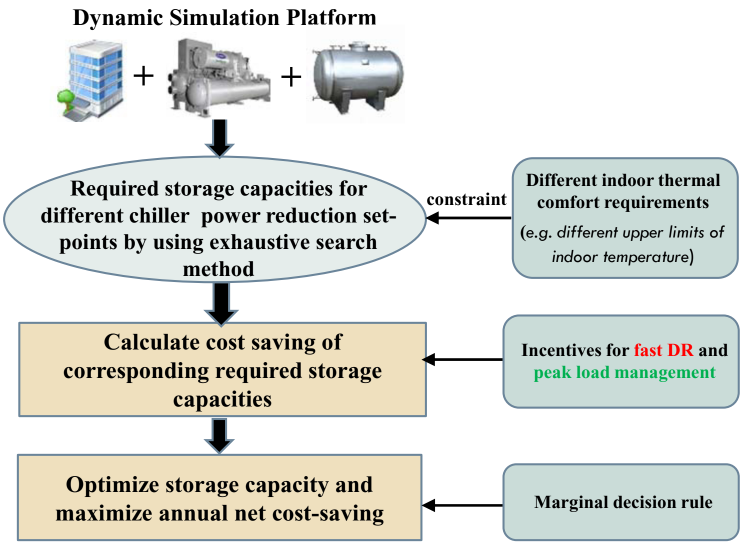


Fig.1 Methodology flowchart

As shown in Fig.1, a dynamic simulation test platform is built first, which include different dynamic models, such as chiller, PCM storage tank, building and et al. The required capacities of CTES for different chiller power reduction set-points by using exhaustive search method are resulted under control of the developed fast power demand response strategy using active and passive building CTES [7]. The different indoor thermal comfort requirements from building users, i.e. different upper limit of indoor temperature, are assumed to be the constraint. In the next step, the cost saving of the resulted storage capacities are calculated by introduction of incentives for both fast DR and PLM. A optimal design method by using marginal decision rule is introduced from [8] to optimize the capacity of active CTES and to determine the corresponding maximum annual net cost saving. As shown in Fig.2, the effects of storage capacity on maximum annual net cost saving are illustrated. The annual net cost saving (life-cycle cost saving) is the difference between annual operating cost saving and the average annual system cost. Q_{opt} is the optimal storage capacity that leads to the maximum annual net cost saving over the life cycle when the difference between annual operating cost saving and average annual system cost is the maximum.

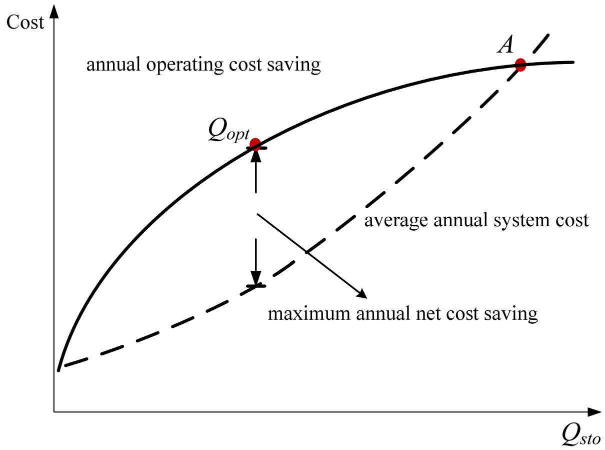


Fig.2 Flowchart of the developed fast demand response strategy

3. Cost benefits for peak load management and fast demand response

An electricity price structure in Guangzhou in South China, as listed in Table 1, is selected as the example to demonstrate the economic benefits from PLM. The whole pricing duration is divided into three periods: high price period, moderate price period and low price period.

Table 1 An electricity price structure in Guangzhou in South China

Location	Electricity price (USD/kWh)		
	High price period (14:00 a.m.to 17:00 p.m.)	Moderate price period (8:00 a.m. to 14:00 a.m.; 17:00 p.m. to 24:00 p.m.)	Low price period (0:00 a.m. to 8:00 a.m.)
Guangzhou	0.13	0.09	0.05

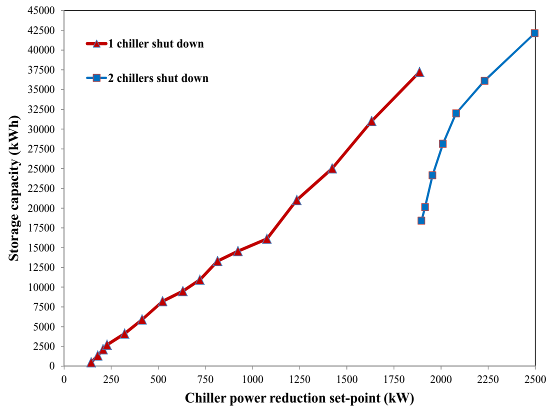
Table 2 A demand response program of NEISO

Program	Duration of DR event	Minimum reduction	Incentive	
			Energy payment	Capacity payment
Real-Time Demand Response (RTDRP)	2 hours	100 kW	500 USD/MWh	$4.1/kW per month

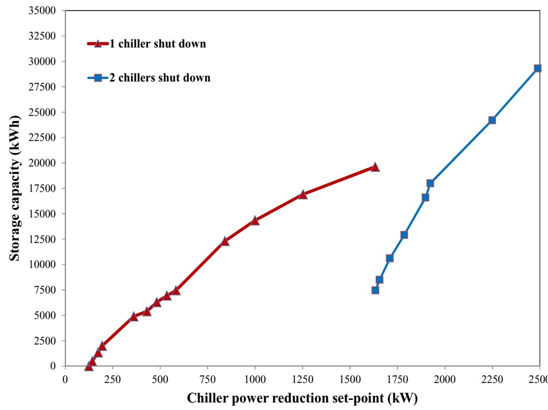
Normally the benefits for demand response largely depend on the financial structure of the DR program which is provided by ISOs/RTOs (grid management). An existing DR program of ISO New England (NEISO) [9], called Real-time Demand Response (RTDRP), as listed in Table 2, in U.S. is used in this study to demonstrate the economic benefits of fast demand response. The incentive paid to customers consists of two parts: One is the energy payment and the other is the (monthly) capacity payment. For instance, if the predetermined power reduction capacity is 400 kW, the capacity payment to the customer is 1640 (400×4.1) USD per month at least even though no DR event actually happens. If the required reduction is 300 kW and the duration is 2 hours in one DR event, the energy payment is 300 USD

(300×2×0.5) per event. Therefore, the total monthly payment is 1940 USD if the DR event happens once in this month. It was assumed that the frequency of DR events is six in one year in this study which accords with the historical frequency of DR event introduced from [10].

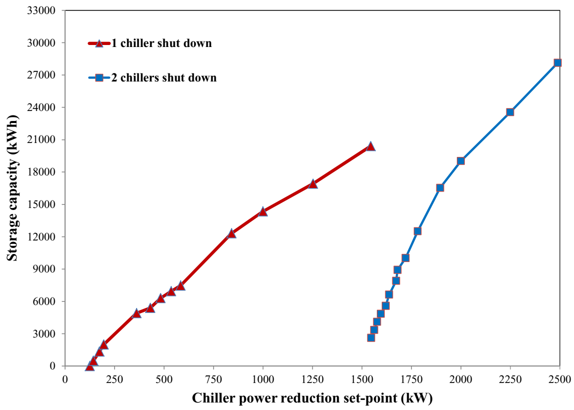
4. Case studies



(a) Indoor temperature set-point upper limit of 23°C



(b) Indoor temperature set-point upper limit of 24°C

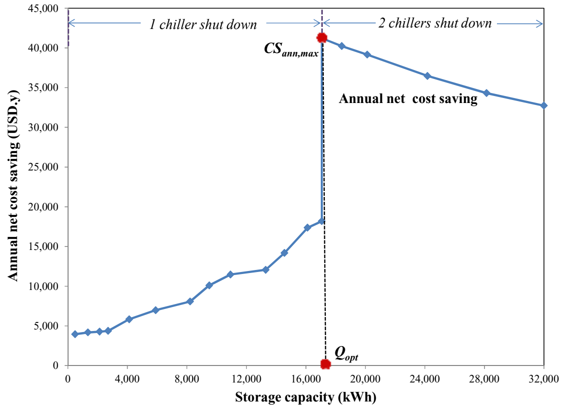


(c) Indoor temperature set-point upper limit of 25°C

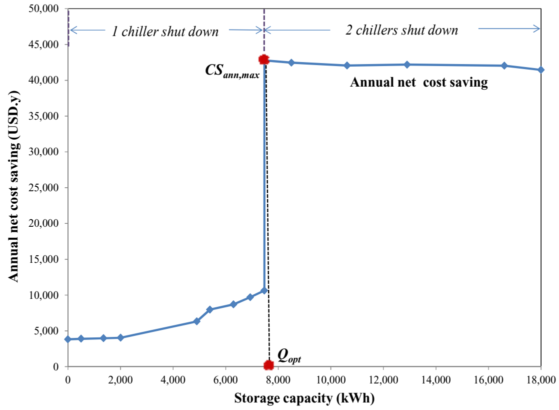
Fig.3 Required capacity of active CTES for different chiller power reduction set-point

Since the cost saving from PLM is proportional to the capacities of active CTES, which are determined under control of the fast DR strategy, it is necessary to investigate the effects of different upper limits of indoor temperature set-point and chiller power reduction set-points on the required capacities of active CTES first. The developed fast DR control with exhaustive search method was accordingly used to determine the required capacities. The simulation results of the required capacities of active CTES for different chiller power reduction set-points under different upper limits of indoor temperature set-point during the DR event are shown in Fig. 3. As the chiller power reduction set-points increase, the required capacities of active CTES increase when the number of chiller required to be shut down is the same. The chiller has a nominal cooling capacity of 7,230 kW each.

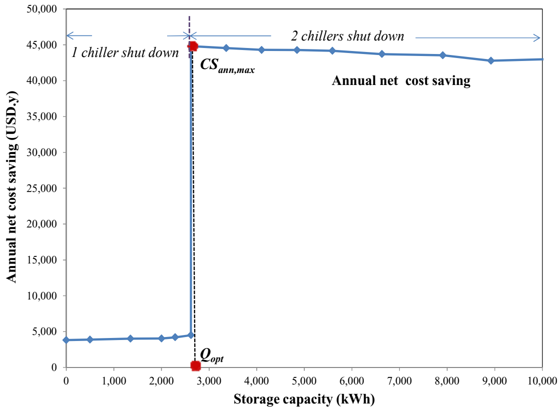
The annual net cost savings of active CTES for building demand management under different upper limits of indoor temperature set-point are shown in Fig. 4. $CS_{ann,max}$ is the maximum annual net cost saving and Q_{opt} is the optimal capacity of active CTES. It can be found that the annual net cost saving increases when one chiller is shut down with the increase of the required capacity of active CTES.



(a) Indoor temperature set-point upper limit of 23˚C



(b) Indoor temperature set-point upper limit of 24˚C



(c) Indoor temperature set-point upper limit of 25˚C

Fig.4 Annual net cost saving of active CTES

Table 3 Results of storage capacity optimization for different indoor thermal comfort requirements

Upper limits of indoor temperature set-point (˚C)	23	24	25
Optimal Chiller power reduction set-points (kW)	-	-	-
Optimal capacity of active CTES (kWh)	17,066	7,473	2,618
Average demand shed (kW)	1,886	1,634	1,547
Percentage of daily cooling load (%)	6.7	3.0	1.0
Maximum annual net cost saving (USD·y)	41,221	42,779	44,808

Meanwhile, when the number of chiller required to be shut down increases, the total annual cost saving has a stepped increase since the annual income from fast DR largely increases. Therefore, $CS_{ann,max}$ is achieved where two chillers are shut down and chiller power reduction set-points are not set. The resulted optimized storage capacities and corresponding optimal chiller power reduction set-points are listed in Table 3. It should be noted that the resulted Q_{opt} is normally less than 7% of the typical daily cooling load.

5. Conclusions

The capacity of active CTES is optimized and the corresponding life-cycle cost saving potential is determined for building demand management. The overall effects of both control modes of active CTES are also analysed. The simulation results show that substantial life-cycle cost saving can be obtained with relative small scale active CTES, i.e. 6.7%, 3,0% and 1.0% of daily cooling load based on the different indoor thermal comfort requirements. It is the first investigation of the significant cost saving potential of active CTES for both fast demand response and peak load management.

Acknowledgements

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Biography

Fu Xiao is an associate professor in Department of Building Services Engineering at The Hong Kong Polytechnic University. Dr. Xiao is an active researcher in the areas of building energy management, building system diagnosis, big building operation data analysis as well as novel and energy efficient air conditioning technologies. Dr. Xiao has published over 70 SCI journals and secured a large amount of competitive research funding in the capacity of principal investigator.