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Application of Cold Thermal Energy Storage (CTES) for building demand management in hot climates

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Highlights

- A new index, *Savings per energy unit*, is defined to assess the effectiveness of CTES.
- CTES systems were used to perform demand management strategies, removing partial load operations and shaving peak loads
- CTES were used to perform price arbitrage, exploiting the difference between peak and off peak electricity rate in Singapore
- Results showed that is possible to enhance the efficiency of the whole system, achieving both energy and economic savings
- Depending on the sizing scenario, the pay back periods ranged between a minimum of 8.9 and 16 years.

Abstract

This paper investigates the feasibility of Cold Thermal Energy Storage (CTES) for building demand management applications in hot climate characterized by a cooling season lasting all year long. An existing office building, located in Singapore, serves as case study. The CTES is coupled to the existing cooling systems in order to address the opportunity of improving overall energy efficiency and to perform price arbitrage, exploiting the spread between peak and off-peak energy tariff. Six different sizes for the CTES are analysed, addressing different percentage of the daily cooling energy demand. A new index, *Savings per energy unit*, is defined to assess the effectiveness of CTES. Results indicate that it is possible to enhance the efficiency of the whole cooling system, achieving both energy and economic savings. The payback periods of the different solutions range between a minimum of 8.9 and a maximum of 16 years. All these aspects make CTES applications a viable option. However, a large amount of space in direct proximity to the building is necessary and, especially in largely urban environment, this is not always available.

35

36 **Keywords:** Cold Thermal Energy Storage; Sensible Heat Storage; Cooling Systems Efficiency;
 37 Price Arbitrage; Demand Side Management; Hot Climates

38

39 NOMENCLATURE

40	AVG	Average
41	$AVG COP_{charge}$	Chillers' average COP during charging phase
42	$AVG COP_{phase}$	Chillers' average COP in the phase considered
43	BMS	Building Management System
44	CH	Chillers
45	CHWP	Chillers Water Pump
46	COP	Coefficient of Performance
47	COP_{charge}	Coefficient of performance during storage charge operations
48	c_p	Specific heat at constant pressure (kJ/kg K)
49	CT	Cooling tower
50	CTES	Cold thermal energy storage
51	E_{Charge}	Energy to charge (kWh _c)
52	E_{charge_daily}	Daily Electricity to Charge (kWh/day)
53	$E_{charge_daily_ctes}$	Daily Electricity Consumption with CTES (kWh/day)
54	$E_{el_cons_daily}$	Daily Electricity Consumption without storage (kWh/day)
55	E_{shift}	Energy to shift (kWh _c)
56	E_{shift_daily}	Daily Electricity to shift (kWh/day)
57	m	Mass of the water within the tank (kg)
58	NODY	Number of operative days per year
59	Q	Energy stored within the storage (kJ)
60	$Savings_{econ_year}$	Yearly Economic savings (US\$)
61	$Savings_{el_y}$	Annual electricity savings (kWh/year)
62	kW _c	Cooling kW
63	kWh _c	Cooling kWh
64	ΔT	Temperature difference
65	η	Storage Efficiency

66 1 Introduction

67 Warming of the climate system is unequivocal. Each of the last three decades has been
68 successively warmer than any preceding decade since 1850, and the concentration of
69 Greenhouse Gases (GHG) have increased. Society can reduce the carbon intensity of energy
70 services, pushing the transition toward low-carbon and/or carbon-neutral technologies [1].
71 Buildings will play an important role since they use about 40% of world's energy demand and
72 25% of global water, while producing one third of total GHG emissions [2]. Energy demand for
73 building cooling will be one the main causes of the growing energy consumption of
74 developing countries located in hot/tropical climates, hence major efforts are necessary to
75 limit their energy demand.

76 Demand Side Management is a mean to increase the efficiency of an entire power system,
77 from generation to the end use, optimizing resources allocation, limiting the peak demand,
78 shaping the loads depending on the necessity of the grid [3].

79 In this context, Thermal Energy Storage (TES) is becoming more and more interesting, since it
80 currently represents one of the most cost-effective solutions to enable demand management
81 strategies [4]; TES enables storing thermal energy (either heat or cold) through a storage
82 medium capable to release the required amount of energy when needed [5].

83 Several studies demonstrated the effectiveness of such systems in different contexts. Cabeza
84 et al. [6] showed the CO₂ mitigation potential of TES systems for different applications
85 (refrigeration, solar power plants, passive system in buildings, greenhouses, dishwashers)
86 and countries: they emphasize the importance of analysing each scenario separately, since
87 different applications impact the energy system in different ways and the results can be
88 heavily affected by the energy mix of the reference country. Arteconi et al. [7] described an
89 existing installation of TES in Italy and performed simulations to prove the potential of
90 different Demand Side Management strategies. Their results showed that the use of TES leads
91 to an increase in energy demand, while costs decrease proportionally with the difference
92 between peak and off-peak energy rates. Schreiber et al. [8] reported the performance of
93 absorption thermal energy storage combined with cogeneration for industrial applications:
94 they proved that, when appropriately integrated with low grade heat sources, TES has the
95 potential to increase the energy efficiency of the industrial process, reducing the primary
96 energy consumption up to 25%. Chvala [9] presented a technical assessment of TES
97 technology to investigate the potential in U.S. federal buildings sector, concluding that TES is a

feasible solution for this category of buildings: thus, TES should be taken into consideration when retrofitting and/or replacement of chillers is carried out. Oró et al. [10] proved the benefits, both energetic and economical, of using a combination of TES and direct air free cooling to satisfy the energy demand of a 1250 kW data centre. The use of direct free cooling is shown to be feasible by itself, however, when using TES in combination with an off-peak electricity tariff, the operational cooling cost can be further reduced. Deforest et al. [11] investigated the economic benefits of Sensible Heat Thermal Energy Storage by simulating its application, for an office building, in four different locations spread across the world (Miami, Lisbon, Shanghai and Mumbai). Their results showed the potential of TES systems in reducing the annual electricity costs (5-15%) and peak electricity consumption (13-33%). All these studies concur to establish that the feasibility of TES applications is related to economic and climatic conditions such as electricity rates/regulations and duration of cold/hot seasons respectively.

The paper differs from the existing literature since it focuses only on cold thermal energy storage (CTES) applied to a hot climate. In particular, it proposes a techno-economic methodology to size CTES according to different management strategies: peak load management, price arbitrage and replacement of chillers partial load operation. The last strategy is particularly interesting since it demonstrated the role of CTES in exploiting the maximum efficiency achievable by the cooling system.

This paper investigates the viability of CTES applications for building demand management in hot climates. The case study is the School of Art, Design and Media (SADM), located within the Nanyang Technological University (NTU) campus in Singapore. Singapore is an interesting case study since it shows the consumption of a developed country in a hot climate.

The proposed study is based on a real set of data for energy demand/consumption¹. A deterministic model has been developed and applied in order to evaluate the energy and economic impact of integrating CTES solutions to the existing cooling systems.

More in details, this paper firstly outlines the case study (e.g. building, cooling plant, energy demand and enhancement opportunities in terms of cooling system efficiency). The sizing methodology, the modelling of CTES, the different scenarios considered and the energy/economic outputs are then discussed in the second part. The results discussion and conclusions are finally reported in the last sections.

¹ The data shown in this paper do not correspond to the real energy demand/measured. The magnitude of the data shown in this article has been modified due to confidentiality reasons. However the output of the analysis is still representative of the real case.

129 2 Methodology and approach

130 2.1 Energy audit

131 The climate in Singapore

132 Singapore lies just north of the Equator near Latitude 1.5 deg N and Longitude 104 deg E. Due
 133 to its geographical location and maritime exposure, Singapore climate is characterised by
 134 uniform temperature and pressure, high humidity and abundant rainfall. There is not a
 135 distinct wet or dry season: rainfall maximum occurs in December and April while the drier
 136 months are usually in February and July. Daily temperature usually ranges between a
 137 minimum of 23-26°C and a maximum of 31-34°C with extremes of minimum of 19.4°C and
 138 maximum of 36°C. With regards to ambient relative humidity (R.H.), the daily R.H. spans
 139 between ≈90% (and above) in the early morning and ≈60 % in the mid-afternoon; the mean
 140 value is ≈84% but during prolonged heavy rain, relative humidity often reaches 100 %.

141

142 *Building*

143 The School of Art, Design and Media (SADM) was built in 2007 as an institutional building
 144 with offices, laboratories, libraries, studios and lecture theatres. The building is located inside
 145 the Nanyang Technological University campus.

146

147 *Cooling system description*

148 Air conditioning for the building is provided by three water cooled chillers. Chillers (CH) A
 149 and B are fitted with centrifugal compressor, using R-123 refrigerant, having a cooling
 150 capacity of 1582 kW each. Chiller C is fitted with a screw compressor, using R-134a
 151 refrigerant, having a cooling capacity of 1055 kW. Each chiller has its own dedicated chilled
 152 water pump, condenser water pump and cooling tower. All the pumps and cooling towers are
 153 fitted with variable speed drive. The speed of the chilled water pumps (CHWP) and cooling
 154 towers (CT) varies from 30 to 50 Hz, while the condenser water pumps (CWP) are operated
 155 with fixed speed at 31Hz. All the air handling units are fitted with electronic air filters and CO₂
 156 sensors. Fresh air supplied to the building is based on return air's CO₂ level. An intelligent
 157 building management system (BMS) is in place to monitor and control the systems operation.
 158 During weekdays, Chiller C is in operation from 7.30 am to 10.30 pm and from 7.30 am to 1.30
 159 pm on Saturdays. Chiller B usually provides the cooling energy demand exceeding the
 160 capacity of chiller C. Chiller A is usually used as backup unit. Usually, the building is closed on

Sundays and Public Holidays (PH) and therefore none of the chillers operates during these periods.

Cooling load and compressor operating efficiency

The present study utilizes real data obtained by monitoring the chillers system over 4 months. Since there is no real alternation in climate between summer and winter in Singapore, the measured cooling load is almost steady throughout the year. Thus, the behaviour of the building over 4 months can be considered representative of a whole year cooling demand. Data were collected with a 1-minute time-step and then aggregated to obtain 15-minute cooling load and COP profiles. Figure 2 shows the daily cooling load profile of each month. Figure 2 shows a regular pattern for the cooling load during the four monitored months: the compressors starts operating at 07:00 and turns off at 23:00.

Three different operating phases can be identified for the cooling system:

- a *peak-load phase* in the morning between 07:00 and 09:00, due mostly to the high quantity of cooling energy necessary to overcome the rise of building temperature occurring during nights and week-ends (the highest cooling energy peaks, around 1580-1600 kW_c occur on Mondays); indeed, since the BMS is programmed to switch-off during both night time and week-ends, the indoor temperature of the building increases because of the high minimum outside temperature (usually around 26°C).
- a *maintaining phase*, between 09:00 and 19:00, that covers most of the day, when the cooling load ranges between 1000-1200 kW_c
- a *partial load phase*, between 19:00 and 23:00, in which there is a reduction of cooling demand due to both the lower occupancy of the building and, to a lesser extent, to the lower outside temperature.

Figure 3 shows the measured coefficient of performance of the system as a function of the cooling demand. The average COP of the chiller system is **5.343** (during office hours between 08.30 and 17:30).

Enhancement opportunities of the technical-economic performance of the cooling system

The energy audit highlights some opportunities to improve the cooling system's techno-economic performance. In particular, three area of intervention have been identified as shown in Figure 4 in which the trend of the cooling load profile for a typical working day is given.

194

195 **First area of intervention, Partial load operation (red area):** the audit showed that Chiller
 196 C has the highest rated COP (refer to Table 2); the datum is confirmed by the experimental
 197 data (refer to figure 3) which show that the cooling system performs better (COP around 5.5)
 198 in the range of 1000-1100 kW_c, whereas its performance decreases at partial load with COP
 199 dropping down to 4.9 at around 700 kW_c. A possible intervention, hence, consists of exploiting
 200 storage technologies to avoid chiller partial load operations.

201 **Second area of intervention, Peak-load management (yellow area):** at the present time, the
 202 BMS automatically manages the three chillers (refer to Table 1) to supply the exact quantity of
 203 cooling energy required. As already emphasized, the cooling system works most of the time in
 204 the “maintaining phase” supplying around 1000-1200 kW_c of cooling energy which is very
 205 close to the 1050 kW_c cooling capacity of chiller C (refer table 1). Hence, a second possible
 206 area of intervention should address the opportunity of exploiting demand side management
 207 in order to reduce the peak load so that only the most performing chiller (chiller C, Table 1) is
 208 operated, with the two others serving as backup units.

209 **Third area of intervention, Price arbitrage:** this intervention is strictly economic and relates
 210 to the exploitation of the *price arbitrage* potential due to the difference between peak and off-
 211 peak electricity tariff in Singapore. The larger the spread between the peak and off-peak
 212 electricity tariff, the larger could be the economic benefit. In Singapore, the off-peak energy
 213 tariff is about 65% of the peak one. The peak period is between 07:00 and 23:00 (figure 5),
 214 matching perfectly the daytime working schedule of the SADM building (figure 2). Hence, the
 215 third area of intervention is to evaluate the techno-economic opportunity of shifting most of
 216 the cooling load from peak to off-peak hours.

217

218 The goal of this paper is to assess the viability of using Cold Thermal Energy Storages (CTES)
 219 to implement demand side management strategies in order to increase the overall efficiency
 220 of the whole cooling system. In particular, the following actions are assessed:

- 221 1- Action 1: CTES is used to replace chiller partial load operations between 19.00 and
 222 23.00. In this way, the performance and profitability of the whole system increases
 223 because the CTES is charged during night time, exploiting both the highest efficiency of
 224 chillers at full load and the off-peak energy tariff.
- 225 2- Action 2: CTES is used to replace the less efficient chillers (chillers A and B) between
 226 07:00 and 19:00. The proposed strategy would be that of running the CTES together

with chiller C (more efficient than chillers A and B); in this case, the CTES would be charged during night time with consequent economic benefit due to price arbitrage.

- 3- Action 3: CTES is sized in order to store as much cooling energy as possible during night time, in order to fully exploit the benefits of price arbitrage.

2.2 CTES SIZING METHODOLOGY

Energy Storage Model

For the techno-economic analysis, a deterministic model is adopted to simulate the behaviour of the storage. The purpose of the model is to evaluate the amount of electrical energy consumed to charge the storage when in operation. The first step consists in defining the amount of cooling energy to be shifted by means of the storage depending on the type of action to be implemented. Once defined the amount of energy to be shifted, the amount of cooling *Energy-To-Charge* is calculated. The Energy-To-Charge can be easily calculated as:

$$E_{Charge} = \frac{E_{shift}}{\eta} \cdot 100 \quad \text{Equation 1}$$

Where η is the charge/discharge efficiency of the storage, also called “round trip efficiency”. The storage efficiency is approximated as a constant parameter, evaluated considering the average charging, discharging and storing losses. The steady-state model does not account for the change in external conditions (e.g. temperature, humidity) which, in the real case, would affect the storage efficiency. This simplified model is particularly suited for a preliminary techno-economic feasibility study in Singapore’s climate characterized by almost steady ambient conditions along the day and across the year.

Cooling energy demand of the building

The assessment of the cooling energy demand of the building is essential for the techno-economic analysis of a CTES. Table 5 shows a list of parameters used to define the daily cooling energy demand of the building. For each month, the daily average cooling energy consumption of the building, the daily average COP (*Daily AVG COP*) of the chillers, the daily AVG electricity consumption (*Daily AVG Electricity Consumption*) and the monthly cooling energy consumption (*Monthly load*) were calculated referring to the real load profiles, obtained by monitoring the cooling system for four months. In order to assess the effect of CTES on the performance of the cooling system, the COP of the system was also calculated for

three different periods of the day: the *Daily AVG COP*, the *Daily AVG COP between 07:00-18:00* and the *Daily AVG COP between 19:00-23:00*.

Table 5 also reports the “monthly surplus” and the “daily average surplus” calculated from real acquired data. These values were calculated in order to address Action 2 (yellow area in Figure 5) in which only the most efficient chiller (chiller C) is operated during peak hours. The “monthly surplus represents the sum of all the “hourly surplus” of a specific month. The “daily average surplus” is calculated as the Monthly Surplus divided by the number of operative days. The “hourly surplus” is defined as the difference between the hourly energy demand and the rated capacity of chiller C (1050 kW_c) and it is calculated for the i^{th} hour as:

$$\text{Hourly Surplus}_i = \text{Energy demand}_i - \text{Rated Capacity of chiller C} \quad \text{Equation 2}$$

Storage Technology and charge/discharge management

The medium considered in the CTES system is water (sensible heat storage) at atmospheric pressure operating with a ΔT of 5°C (temperature range between 7°C when fully charged and 12°C when fully discharged). Figure 7 shows the proposed schematic diagram of the CTES. It is worth noting that the storage can work either in “charge” mode or in “discharge” mode.

The storage efficiency of the CTES system depends on many aspects such as the insulation material, the water diffusion mechanism inside the vessel, the auxiliary systems (pumps, heat exchanger). The thermal energy storage technology review from Irena, indicates that TES systems have an efficiency which spans between 50% and 90% [12]. However, specific tests and experimental analysis carried out by some of the authors of this paper on a real sensible heat thermal energy storage located in Italy, have ascertained a storage efficiency of 85% [7]. The capital cost for the whole system was also calculated as 212 US\$/m³, including the cost for vessel, hydraulic system, compact heat exchanger and civil works. With regard to the operating strategies, TES system usually operates in full storage or partial storage mode. Full storage systems are designed to cover the whole energy demand during peak hours. On the contrary, partial storage systems shift the excess demand from a pre-established threshold and can be used to shave the peaks, to stabilize the variable load of the energy demand or to partially replace the chillers system. CTES operating in full storage mode results in a larger and more expensive design since it aims to completely replace the cooling system during peak hours; this operating mode is usually suitable for large peak/off-peak spreads.

Analysis outputs

The main parameters utilized to assess costs and potential benefits of each proposed solution are the following: storage size, electricity to charge, percentage of electricity saved, economic savings, savings per energy unit (specific savings), estimated capital costs and payback period (Tables 6, 7 and 8). The *Storage size* (m^3) is calculated using the following equation:

$$Q = m c_p \Delta T \quad \text{Equation 3}$$

Where Q represents the daily energy quantity to shift (based on the average working day and on the type of action addressed), expressed in kJ; m is the total mass of water stored in the vessel in kg; c_p is specific heat of water at constant pressure, expressed in kJ/kgK; ΔT is the maximum temperature difference to which the storage medium is subjected.

The Daily Electricity to Charge (kWh/day) represents the amount of electricity consumed to charge the storage. It is related to the Energy to Charge (Equation 1) and the chillers' average COP during charge ($AVG COP_{charge}$). As an example, when addressing the first area of intervention, the charge operations occurs during off-peak hours, with chillers operating at rated capacity and rated COP ($AVG COP_{charge}=6.2$, see Table1).

$$E_{charge_daily} = \frac{E_{charge}}{AVG COP_{charge}} \quad \text{Equation 4}$$

The new Daily Electricity Consumption after the CTES introduction ($E_{charge_daily_ctes}$) is calculated according to Equation 5, being a function of the Daily Electricity to Charge (E_{charge_daily}), the Daily Energy to Shift (E_{shift_daily}) and the COP ($AVG COP_{phase}$) of the chillers in the phase considered (peak load, maintaining, partial load).

$$E_{charge_daily_ctes} = E_{el_cons_daily} - \frac{E_{shift_daily}}{AVG COP_{phase}} + E_{charge_daily} \quad \text{Equation 5}$$

The performance of the chillers can be represented by the Daily AVG COP, either the Daily AVG COP 7:00–18:00 or the Daily AVG COP 19:00–23:00, depending on which portion of the energy demand is being shifted. As an example, when addressing the first area of intervention, shifting the energy to avoid partial load operations (red area, figure 4), the average COP considered is the Daily AVG COP 19:00–23:00.

The Annual *electricity savings* (*kWh_e/year*) are calculated as the difference between the Daily electricity consumption of the cooling system before and after the CTES introduction, multiplied by the Number of Operative Days per Year (NODY).

$$Savings_{el,y} = (E_{el_cons_daily} - E_{charge_daily_ctes}) \cdot NODY \quad \text{Equation 6}$$

The *Economic savings* (US\$) are calculated as the difference between the yearly operative costs before and after the introduction of the energy storage. When evaluating the yearly operative costs the Energy-to-Shift per day, the Energy-To-Charge per day, the spread between peak and off-peak tariffs and the number of operative days per year are taken into account.

$$Savings_{econ_year} = \left(\frac{E_{shift_daily}}{AVG\ COP} - E_{charge_daily} \right) \cdot (PT - OPT) \cdot NODY \quad \text{Equation 7}$$

The *Savings per energy unit* (US\$/kWh_c) is obtained by dividing the Economic savings by the energy capacity of the storage. This is a measure of the effectiveness of the solution.

The *Payback period* (years) represents the main parameter to assess the economic feasibility of an investment: it is evaluated considering the capital costs and the annual Economic savings.

$$Payback\ period = (Estimated\ capital\ costs) / (Economic\ savings) \quad \text{Equation 8}$$

3 Results and considerations

This section presents the main results of the techno-economic study carried out in order to find the optimal sizing of the CTES according to its use in the cooling system management strategy. It was assumed that the new cooling system (Figure 8), integrating the cold storage and the present chillers, had to satisfy a daily average cooling energy demand of 12872 kWh_c, considering 275 operative days per year. In particular, 12872 kWh_c was calculated as the average cooling energy demand in the four monitored months and it represents the 100% of the design daily average cooling energy demand. Figure 8 shows the simplified scheme of the new cooling system integrating CTES.

Storage sizing to avoid partial load operations (first area of intervention)

In this case, the storage was sized to manage the average cooling energy demand of the SADM building between 07:00 and 23:00 period, which corresponds to 2800 kWh_c (Energy-to-shift) of cooling energy during an average working day.

The cold storage works in “total storage” mode: during off-peak hours the most efficient chiller (chiller C, Table 1) charges the storage; from 08:00 to 19:00 the existing chillers supply the cooling energy required, with an average COP of 5.4; from 19:00 to 23:00 the energy demand is completely satisfied by the cold storage (Figure 9). Indeed, without the CTES, the chillers worked during peak hours in the red zone of Figure 9, with an average COP of 4.8. Using the CTES, 2800 kWh of cooling energy can be shifted in off-peak hours, with chillers operating at rated capacity with a higher average COP of 6.2. The new cooling system does achieve more than 11 MWh of electricity savings per year. In order to store 2800 kWh of cooling energy a 482 m³ vessel is necessary. The investment cost can be estimated as 212 US\$/m³ while the economic savings are calculated as 11480 US\$ (that is a 4.1 US\$/kWh). The estimated payback period is 8.9 years (Table 6).

Sizing the storage to replace the backup chillers (second area of intervention)

In this case, the storage was designed to shift the “daily average surplus” in the average working day. In this scenario CTES works in “partial storage” mode: during off-peak hours chiller C charges the storage at rated capacity, with a COP of 6.2; from 08:00 to 19:00 chiller C supplies the cooling energy required to the building at its maximum capacity (1050 kW); whenever the energy demand exceeds the 1050 kW limit, the cold storage provides the surplus energy required (Figure 10). The improvements in the overall cooling system efficiency are limited: the benefits of charging the storage during night, at rated COP, are almost completely lost in the storing process. Under the economic point of view this scenario entails a shifting of 731 kWh of cooling energy for a volume of the storage of 126 m³ and an estimated investment cost of 102184 US\$. The yearly Economic savings are calculated as 1660 US\$ (2.27 \$/kWh), for a payback period of 16 years.

Storage sizing for price arbitrage strategies (third area of intervention)

This sizing scenario is meant to exploit the price arbitrage potential due to the difference between peak and off-peak electricity tariffs in Singapore.

The proposed operating schedule is a sort of “hybrid storage” mode, which is a combination of the two previous operating strategies: during off-peak hours the chillers work to charge the storage; from 08:00 to 19:00 the storage works in “partial storage” mode, using the stored energy to compensate the “daily average surplus” (yellow area in Figure 11); from 19:00 to 23:00 the storage works in “total storage” mode so that the cooling energy demand relies uniquely on the cold storage (red area in Figure 11).

This scenario was evaluated for four different percentage of the daily energy demand: 27%, 50%, 75% and 100%. The 27% of the total energy demand represents the minimum storage capacity necessary to address both the first and the second area of intervention (red and yellow areas in Figure 9).

Regardless of the percentage of the daily energy demand being shifted, priority is always given to the period between 19:00 and 23:00 to avoid the chillers working at lower COP (red area in Figure 11).

Using the “hybrid storage” operating strategy, shifting the 100% of the daily demand, 32180 US\$ of savings per year were estimated, with a 2.5 US\$/kWh rate. To shift this quantity of cooling energy a 2214 m³ vessel is necessary for an estimated investment cost of 469371 US\$. Table 8 shows the model outputs related to the other suggested designs.

Comments

The results, showed in Table 6 to 8, demonstrate that the introduction of CTES entails a reduction of the electricity consumption of the cooling system for most of the suggested scenarios. At a first sight, this result could be unexpected since the energy storage introduces an inefficiency in the whole cooling system. This result is explained by the fact that, in these two scenarios, the CTES allows the optimal management of the cooling system achieving a higher average COP able to compensate the inefficiency introduced by the storage itself. In the 75% and 100% scenarios, Chillers A, B and C have to work together, thus the AVG COP_{charge} is much lower (Daily AVG COP between 07:00 and 18:00, table 5) than in the other scenarios in which the cooling system can work with the COP of the most performing chillers. The *Savings per energy unit* gives an indication of which design is the most effective. The sizing scenario described in Table 6 is the best with savings of 4.1 US\$/kWh. In this case the whole amount of Energy-To-Shift exploits both the peak/off-peak price spread and the cooling efficiency enhancement moving from the lower COP value due to partial load operations (Daily average COP 19:00-23:00, table 5), to the rated COP of chiller C (6.2).

Table 7 describes the suitable CTES size to replace chillers A and B in addressing the demand surplus from 07:00 to 19:00; the results show that the *Savings per energy unit* (2.27 US\$/kWh) and *Annual electricity savings* are negligible. Indeed, this scenario is the only one that does not address the partial load operations, thus offering much less potential improvement of the cooling system performances. However, it still manages to produce savings and once the existing system starts getting older or less efficient, such a design can be taken into consideration to replace the chillers, downsizing the installed equipment.

The 27% case is of particular interest since it represents the minimum investment to address both the first and second area of intervention described in Section 2.1. This design is able to exploit both the profitable aspects discussed before, proving itself extremely effective (2.76 US\$/kWh of savings per energy unit).

The 75% and 100% cases, as already mentioned, are the most inefficient designs, since they need the three chillers to work together to charge the storage, resulting in a lower average COP: the introduction of the storage actually increases the energy consumption of the cooling system which leads lower *Savings per energy unit* (2.57 and 2.50 US\$/kWh).

From a purely economic point of view, the results shown in Tables 6, 7 and 8 demonstrate the viability of the suggested solutions. The payback periods stand between a minimum of 8.9 years and a maximum of 16 years. An expected good result considering that the case study presents some of the ideal conditions for CTES applications: a large, steady, cooling demand throughout the year. Moreover, the cooling demand profiles perfectly match with the peak period of Singapore's electricity tariff. On the other hand, the spread between peak and off-peak tariff is not particularly large and it does not represent an adequate economic incentive to shift the loads to off-peak hours. All considered, CTES applications seem appealing in Singapore. The main limit of CTES technology with sensible heat is the low energy density value, which results in large amount of space requirements. This work showed that the storage volume ranges from 482 m³ (first area of intervention) to 2214 m³ in the case of complete day-night shifting of the cooling energy demand. A large amount of space in direct proximity of the building is necessary and, especially in highly populated cities like Singapore, is not always available.

4 Conclusions

This work has demonstrated the feasibility of CTES for building demand management in hot climate. The School of Art, Design and Media building, located within NTU campus in Singapore, served as case study.

In the first part, the building characteristics and the demand profiles were analysed to search for energy efficiency improvement opportunities. Three possible areas of intervention were identified: (i) to reduce/remove partial load operations; (ii) to exploit demand management strategies in order to reduce peak loads, so that only the most performing chiller needs to operate; (iii) to perform price arbitrage, exploiting the difference between peak and off-peak electricity rate in Singapore.

Six scenarios were described, addressing different percentage of the average daily demand. For each scenario the appropriate size of CTES and the key performance indicators were evaluated. Results indicate that it is possible to enhance the efficiency of the whole system, achieving, for most of the cases, both energy and economic savings. In particular, the most effective solution is that with the CTES replacing the cooling system partial load operation. The payback periods of the different scenarios stand between a minimum of 8.9 years and a maximum of 16 years. All these aspects make CTES applications appealing. However, sensible heat technology is characterized by a low energy density value, which results in large amount of space requirements. For the case study, the storage volume ranges from 482 m³ to 2214 m³, thus a lot of space in direct proximity to the building is necessary and, especially in highly populated cities like Singapore, is not always available.

Bibliography

- [1] International Panel on Climate Change, "Climate change 2014: Synthesis report," IPCC, Geneva, Switzerland, 2014.
- [2] World Business Council For Sustainable Development, "Transforming the market: energy efficiency in the buildings," WBCSD, 2009.
- [3] G. Strbac, "Demand side management: Benefits and challenges," *Energy Policy*, vol. 36, pp. 4419-4426, 2008.
- [4] A. Arteconi, N. Hewitt and F. Polonara, "State of the art of thermal storage for demand-side management," *Applied energy*, vol. 93, pp. 371-389, 2012.
- [5] I. Dincer and M. A. Rosen, *Thermal Energy Storage: Systems and Applications*, 2nd Edition, Wiley, 2010.
- [6] L. F. Cabeza, L. Mirò, E. Orò, A. De Gracia, V. Martin, A. Kronauer, C. Rathgeber, M. M. Farid, H. O. Paksoy, M. Martinez and A. I. Fernández, "CO₂ mitigation accounting for

- Thermal Energy Storage (TES) case studies," *Applied energy*, no. 155, pp. 365-377, 2015.
- [7] A. Arteconi, J. Xu, E. Ciarrocchi, L. Paciello, G. Comodi, F. Polonara and R. Wang, "Demand Side Management of a Building Summer Cooling Load by Mean of a Thermal Energy Storage," *Energy Procedia*, vol. 75, pp. 3277-3283, 2015.
- [8] H. Schreiber, S. Graf, F. Lanzerath and A. Bardow, "Absorption thermal energy storage for cogeneration in industrial batch processes: Experiment, dynamic modeling and system analysis," *Applied Thermal Engineering*, vol. 89, pp. 485-493, 2015.
- [9] W. Chvala, "Technology potential of Thermal Energy Storage (TES) systems in Federal Facilities," Office of energy efficiency and renewable energy, 2001.
- [10] E. Orò, V. Depoorter and N. S. J. Plugrad, "Overview of direct air free cooling and thermal energy storage potential energy savings in data centres," *Applied thermal engineering*, vol. 85, pp. 100-110, 2015.
- [11] N. DeForest, G. Mendes, M. Stadler, W. Feng, J. Lai and C. Marnay, "Thermal energy storage for electricity peak demand mitigation: a solution in developing and developed world alike," in *ECEEE 2013*, Belamba Les Criques, France, 2013.
- [12] IRENA - ETSAP, "Thermal energy storage: technology brief," 2013.
- [13] K. Bradbury, L. Pratson and D. Patino-Echeverri, "Economic viability of energy storage systems based on price arbitrage potential in real time U.S. electricity market," *Applied Energy*, no. 114, pp. 512-519, 2014.
- [14] U.S. Department of Energy, "2012 buildings energy data book," Office of Energy Efficiency and Renewable Energy, 2012.
- [15] B. Cui, D.-c. Gao, S. Wang and X. Xue, "Effectiveness and life-cycle cost-benefit analysis of cold storages for building demand management for smart grid applications," *Applied energy*, no. 147, pp. 523-535, 2015.
- [16] B. Rismanchi, R. Saidur, G. Boroumandjazi and S. Ahmed, "Energy, exergy and environmental analysis of Cold Thermal Energy Storage (CTES) systems," *Renewable and sustainable energy reviews*, no. 16, pp. 5741-5746, 2012.
- [17] P. Arce, M. Medrano, A. Gil, E. Oro and L. F. Cabeza, "Overview of Thermal Energy Storage (TES) potential energy savings and climate change mitigation in Spain and Europe," *Applied energy*, vol. 88, no. 8, pp. 2764-2774, 2011.
- [18] M. Miller, M. Johns, E. Sortomme and S. Venkata, "Advanced integration of distributed energy resources," in *Power and energy society general meeting, 2012, IEEE*, 2012.

- [19] M. Akorede, H. Hizam and E. Pouresmaeil, "Distributed energy resources and benefits to the environment," *Renewable sustainable energy reviews*, no. 14, pp. 724-734, 2010.
- [20] R. Pundineh and T. Jamasb, "Distributed generation, storage, demand response and energy efficiency as alternatives to grid capacity enhancement," *Energy policy*, no. 67, pp. 222-231, 2014.
- [21] S. Bellan, T. E. Alam, J. Gonzàles-Aguilar, M. Romero, M. M. Rahman, D. Y. Goswami and E. K. Stefanakos, "Numerical and experimental studies on heat transfer characteristics of thermal energy storage system packed with molten salt PCM capsules," *Applied thermal engineering*, vol. 90, pp. 970-979, 2015.
- [22] N. Deforest, G. Mendes, M. Stadler, W. Feng, J. Lai and C. Marnay, "Optimal deployment of thermal energy storage under diverse economic and climate conditions," *Applied energy*, vol. 119, pp. 488-496, 2014.
- [23] A. Girard, E. Jadraque Gago, T. Muneer and G. Caceres, "Higher ground source heat pump COP in a residential building through the use of solar thermal collectors," *Renewable energy*, vol. 80, pp. 26-39, 2015.
- [24] S. Ruiz-Romero, A. Colmenar-Santos, F. Mur-Pérez and A. Lòpez-Rei, "Integration of distributed generation in the power distribution network: the need for smart grid control systems, communication and equipment for a smart city - Use cases," *Renewable and sustainable energy reviews*, vol. 38, pp. 223-234, 2014.
- [25] J. L. Mathieu, M. E. Dyson and D. S. Callaway, "Resource and revenue potential of California residential load participation in ancillary services," *Energy Policy*, vol. 80, pp. 76-87, 2015.
- [26] Energy Market Authority, "Singapore Energy Statistics 2015," Singapore, 2015.

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Figure 1: The building cooling system

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Figure 2: Trend of the cooling profiles (kW) in the four monitored months

Figure 3: Coefficient of Performance of the chillers system

Figure 4: Cooling load profile for a typical normal operative day

489 Figure 5: Qualitative diagram representing the daily evolution of the electricity tariff in Singapore

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492 Figure 6: Energy storage model

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495 Figure 7: A typical CTES system's configuration.

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498 Figure 8: The new cooling system integrating the existing chillers and the CTES

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Figure 9: New cooling load of the chillers (in blue) with storage sized to avoid partial load operations (red zone)

Figure 10: New cooling load of the chillers (in blue) with storage sized to avoid peak load operations (in yellow)

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507 *Figure 11: New cooling load of the chillers (in blue) with storage sized to cover 27% of the overall cooling demand*

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512 *Table 1: Specification of Chillers*

Parameter	CH (A - B)	CH (C)
Refrigerant	R-123	R-134a
Cooling Capacity	1582 kW _c	1055 kW _c
Year of manufacture	2006	2003
Chiller rated electrical power	270 kW	169 kW
Chilled water supply temperature (Design)	6.7 °C	6.7 °C
Chilled water return temperature (Design)	12.2 °C	12.2 °C
Chilled water flow (Design)	68.5 l/s	45.2 l/s
Condenser water supply temperature (Design)	29.5 °C	29.4 °C
Condenser water return temperature (Design)	35.0 °C	34.6 °C
Condenser water flow (Design)	85.7 l/s	56.78 l/s
Rated Coefficient Of Performance (COP)	5.8	6.2

513 *Table 2: Specification of Chilled water pumps*

Parameter	CHWP A - B	CHWP C
Design flow rate	68.5 l/s	45.5 l/s
Design pump head	28.1 m	35.0 m
Design motor power	37.0 kW	30.0 kW

514 *Table 3: Specification of Condenser water pumps*

Parameter	CWP A - B	CWP C
Design flow rate	85.7 l/s	58.3 l/s
Design pump head	27.0 m	25.0 m
Design motor power	37.0 kW	30.0 kW

515 *Table 4: Specification of Cooling Towers*

Parameter	CT
Cooling capacity	1973 kW
Design flow rate	85.7 l/s
Design condenser water supply temperature	29.5 °C
Design condenser water return temperature (°C)	35.0 °C
Design wet bulb temperature	26.7 °C
Design motor power	3 x 7.5 kW

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517 *Table 5: Total monthly consumption, average daily consumption and COP values for the reference periods*

Referring month	Monthly load (kWh _c)	Daily AVG consumption (kWh _c)	Daily AVG Electricity Consumption (kWh _c)	Daily AVG consumption 19:00-23:00 (kWh _c)	Daily AVG COP	Daily AVG COP 7:00-18:00	Daily AVG COP 19:00-23:00	Monthly surplus (kWh _c)	Daily AVG surplus (kWh _c)
March	344801	12771	2425	2714	5	5.2	4.3	9242	420
April	390061	14447	2744	2742	5.4	5.5	5.1	18273	731
May	359861	12409	2357	2547	5.3	5.4	5.1	6941	365
June	344000	11862	2253	2550	5.4	5.4	4.9	7332	407

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519 *Table 6: Main analysis results for a storage dedicated to the first area of intervention*

Parameter	Value
Energy To Shift	2800 kWh
Annual electricity savings	11520 kWh
% of the daily demand stored	21.7 %
Storage Size	482 m ³
Economic Savings	11480 US\$/year
Savings per energy unit	4.1 US\$/kWh
Estimated cost	102184 US\$
Payback	8.9 years

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521 *Table 7: Main analysis results for a storage dedicated to the second area of intervention*

Parameter	Value
Energy to Shift	731 kWh
Annual electricity savings	20 kWh
% of the daily demand	5.7 %
Storage Size	126 m ³
Economic Savings	1660 US\$/year
Savings per energy unit	2.27 US\$/kWh
Estimated cost	26653 US\$
Payback	16 years

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523 *Table 8: Main analysis results for four different sizing scenarios*

Parameter	27% of the daily demand	50% of the daily demand	75% of the daily demand	100% of the daily demand
Energy To Shift	3531 kWh	6436 kWh	9654 kWh	12872 kWh
Annual electricity savings	10505 kWh	6932 kWh	-72144 kWh	-101092 kWh
Storage Size	608 m ³	1107 m ³	1661 m ³	2214 m ³
Economic Savings	14124 US\$	23427 US\$	24811 US\$	32180 US\$
Savings per energy unit	4 US\$/kWh	3.64 US\$/kWh	2.57 US\$/kWh	2.50 US\$/kWh
Estimated cost	128896 US\$	234685 US\$	352132 US\$	46937 US\$
Payback	9.1 years	10 years	14.2 years	14.6 years

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