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Strategy for Energy Savings in a Commercial Building Air-conditioning System with Chilled Water Storage: A Case Study in a Retail Mall in Thailand

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Abstract

In this study, a commercial retail mall is used as a case study to integrate a chilled water storage (CHWS) with the existing chilled water system to reduce electrical energy consumption and capitalize on the economic benefits of electrical energy saving cost and the differential between on-peak and off-peak tariffs. This study aims to improve the chiller efficiency in three operating strategies: full storage, partial storage load leveling, and partial storage demand limiting, by operating the chillers at optimal part load conditions. Technical and economic assessments were conducted to determine the necessary storage capacity and appropriate operational strategies. In comparison to the existing operation, which uses two 800 RT chillers continuously during on-peak hours and one chiller operating at 20-30% capacity during off-peak hours, the proposed systems: three 800 RT chillers with a 9,150 m³ tank for full storage, one 800 RT and one 260 RT chiller with a 3,292 m³ tank for partial load leveling, and two 800 RT chillers with a 4,987 m³ tank for partial demand limiting, demonstrate significant potential to reduce electrical energy consumption. The full storage strategy achieves the lowest electrical energy consumption, followed by partial demand limiting and partial load leveling. Economically, partial demand limiting strategy emerges as the most feasible, providing a payback period of 7.42 years and an internal rate of return (IRR) of 14.92%. This is more favorable compared to payback periods of 8.6 and 9.65 years and internal rate of return of 12.08 and 10.33% for partial load leveling and full storage strategies, respectively.

Keywords: *chilled water storage; energy saving; economic analysis; operating strategies*

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1. Introduction

The International Energy Agency reports that since 2000, the energy demand for space cooling has grown at an average annual rate of approximately 4%. In 2022, energy consumption for space cooling increased by more than 5% compared to 2021, driven by strong post-pandemic economic recovery and unusually warm summer temperatures. In commercial buildings, air-conditioning (AC) system chillers consume the most power during peak load, accounting for more than 40% of total air conditioning energy use, primarily in the afternoon (Saidur et al., 2011). In Thailand, air-conditioning systems account for up to 60% of all building energy usage due to Thailand's tropical climate zone (Sreewirote, & Ngaopitakkul, 2019). Therefore, peak demand management is essential for mitigating peak electricity demand through strategies such as peak load shifting and reduction.

Over the past two decades, chilled water energy storage (CHWS) technology has been adopted and recently advanced as a method to conserve energy by shifting peak electricity demand from peak hours to off-peak hours. The integration of CHWS into conventional AC systems can significantly reduce electrical energy consumption and costs by taking advantage of lower electricity tariff rates and peak demand shifting.

Additionally, CHWS systems offer several significant advantages over other systems. These include compatibility with existing cooling systems such as chillers with air or water-cooling, which can be used without special equipment or with dedicated storage pumps; simpler controls compared to ice and phase change systems; the ability to serve as an emergency fire protection resource and a standby mode for cooling during power supply failures; and lower capital cost (Dorgan, & Elleson, 1993).

The CHWS technology has three main operating strategies: full storage partial load leveling, and partial demand limiting. According to Dincer (2002), the full storage method is suitable in the cases where high peak demand prices are in effect, and attractive incentives are available with short peak load duration. Partial load leveling is appropriate when the load remains high for extended periods and the peak cooling demand is significantly higher than the average cooling load. This approach allows for a reduction in the size and cost of storage tanks, chillers, and associated pumps. However, it results in a smaller decrease in daytime electricity consumption compared to other storage systems. In the partial demand limiting strategy, chillers are designed to operate at reduced capacities, such as 25%, 50%, or 75% during peak hours. Generally, the system size, cost, and energy demand savings for this approach fall between those of full storage and load leveling.

The literature includes numerous studies on the incorporation of conventional AC systems into CHWS systems with the implementation of three main operating modes in various building types. Boonnasa, & Namprakai (2010) studied the application of CHWS in a university building to determine the optimal chilled water storage capacity and operating strategies for AC loads under different electricity rates. They concluded that the optimal design involved operating two 450 RT chillers at a constant load for 24 hours, with a storage capacity of 9413 RT-h (5175 m³ volume). This configuration could shift 35.7% of energy consumption from peak to off-peak periods. The economic analysis revealed a payback period (PB) of 10 y, an internal rate of return (IRR) of 21%, and a net present value (NPV) of 0.834 million USD compared to the existing system. Rahman et al., (2011) also investigated the use of CHWS in an institutional building in Australian subtropical climate. Their findings indicated that full, partial load leveling, and demand-limiting chilled storage systems could reduce electricity costs by up to 61.19%, 33.94%, and 50.26%, respectively, compared to conventional air-cooled chillers. Zhang et al., (2011) studied the integration of a new chilled water storage tank for 19 buildings served by four chiller plants in the U.S. They evaluated eight different tank sizes using a typical time-of-use (TOU) rate structure and determined that a 3.5 million-gallon (13,249 m³) tank was the most cost-effective, offering the shortest payback period. The optimal strategy focusing on the selected tank size was full storage during summer and storage-priority during winter. Sebzali et al., (2012) calculated the life cycle cost (LCC) of chilled water thermal storage (CWTS) and traditional AC systems to determine the most economical storage solution for the Ministry of Electricity and Water (MEW) and the customer for cooling buildings in Kuwait climates. The author used three operating strategies, including full storage, partial load levelling, and partial demand restriction with a 50% capacity reduction. In contrast to 50% demand limitation and complete storage, they observed that, in the absence of a low electricity tariff rate, the CWTS with partial load levelling was the best storage solution for MEW and consumer. In another studie, Sebzali et al., (2014) explored the implementation of the CHWS AC system in a clinic building under the Kuwait climate, finding that, under design day conditions, peak electricity demand and annual energy consumption for AC systems decreased by 36.7% to 87.5% and 4.5% to 6.9%, respectively, compared to conventional AC systems. The study concluded that the most cost-effective approach was to use a load-leveling strategy, which resulted in the lowest life cycle cost when compared to full storage and 50% demand limiting strategies.

Rismanchi et al. (2012) explored the cost-saving potential of using an ice thermal storage (ITS) system in an office building in Malaysia over next 20 years. Their findings indicated that a full storage system could reduce annual AC system costs by up to 35%, whereas partial storage load leveling achieved a savings of only 8%. The payback period ranged from 3 to 6 years for full storage and from 1 to 3 years for load leveling. Comodi et al., (2016) examined the feasibility of using Cold Thermal Energy Storage (CTES) with a cooling system for managing building demand in Singapore with year-round cooling needs. Not only the energy efficiency could be enhanced but also there was an advantage on cost saving due to the price difference between peak and off-peak energy tariffs. They investigated six different storage sizes corresponding to different percentages of daily cooling energy demand, with payback periods for the various solutions ranging from 8.9 to 16 years. Shaibani et al., (2019) conducted a thermo-economic analysis of a factory refrigeration system, comparing two Cold Thermal Energy Storage (CTES) modes: ice storage and cold-water storage. The study aimed to explore ways to reduce energy consumption compared to conventional systems without storage. They found that full cold-water storage was the most optimal solution, with a 14-year payback period. Alhikami et al., (2024) investigated the feasibility of implementing CTES in a hospital building, employing six storage strategies: full storage, load leveling storage, and partial storage at 30%, 50%, 70%, and 90%. The study assessed electricity consumption, energy costs, and chiller performance across various scenarios to identify the most effective strategy. They concluded that leveling storage was the best option for new cooling systems, achieving annual energy savings of up to 10.5%. However, for existing systems, partial storage at 30% proved to be the optimal strategy, with higher energy savings up to 13% annually.

The existing literature reveals that most studies on CHWS systems have concentrated on their application in buildings such as offices, universities, institutional facilities, and hospitals. However, few case studies have been conducted in commercial buildings like retail malls, particularly in hot and humid climates such as Thailand, which is the primary focus of this research. Additionally, many studies have shown that chillers are typically operated at full load in full storage and partial load leveling strategies, except in partial demand limiting, where chiller efficiency tends to decrease due to operation at less than half load during off-peak hours. This study examines the technical implementation of CHWS systems with three operational strategies: full storage, partial load leveling, and partial demand limiting, by operating the chillers at optimal part load conditions integrated with the existing AC system of retail mall. Furthermore, the economic benefits of these strategies are evaluated based on electricity tariff structures during peak and off-peak periods to determine the optimal chiller and chilled water storage capacities. The optimum size of the chilled water storage tank can be determined, and the significant potential for reducing electrical energy consumption under electricity tariff structures during peak and off-peak periods can be analyzed.

The existing research primarily focuses on the application of CHWS systems in buildings like offices, universities, institutional facilities, and hospitals. However, there is a lack of case studies on commercial buildings such as retail malls, especially in hot and humid climates like Thailand, which is the focus of this study. Furthermore, previous studies indicate that chillers typically operate at full load in full storage and partial load leveling strategies, whereas efficiency decreases in partial demand limiting due to chiller operation at less than half load during off-peak hours. This research investigates the technical implementation of CHWS systems with three operational strategies: full storage, partial load leveling, and partial demand limiting, by optimizing part load conditions for chillers integrated with the existing AC system of a retail mall. Furthermore, the economic benefits of these strategies are evaluated based on electricity tariff structures during peak and off-peak periods to determine the optimal chiller and chilled water storage capacities. The results can establish the optimum size for the chilled water storage tank and assess the potential for reducing electrical energy consumption under the tariff structures during peak and off-peak periods.

2. Case Study

A retail mall in Thailand, situated in a hot and humid tropical climate with a gross floor area of 30,000 m² and an air-conditioned area of 28,000 m², was chosen to assess the impact of a CHWS-AC system on energy consumption and economics. The outdoor temperature ranges from 34°C to 40°C (Weather Underground, 2024). An hourly cooling load profile, obtained from on-site measurements on a design day, is illustrated in Figure 1, with peak cooling demand during the day and additional load requirements at night for maintaining low temperatures for foodstuffs and small shops. The data were collected during the summer season, from Monday to Sunday, with 1-minute time step capturing the supply and return chilled water temperature as well as the chilled water flow rate. From the data, the cooling load was calculated for each time step using $Q = \dot{m}c_p\Delta T$. Then, the data were aggregated to obtain hourly cooling load by averaging the loads over each hour to reflect the cooling demand on an hourly basis. The variation of the load profile may not differ significantly during the summer and winter season, therefore the profile is assumed to remain consistent throughout the year. In the current chilled water system as shown in Figure 2, two 800 RT units run continuously to satisfy the building’s cooling requirements. During off-peak times with lower cooling demand, only one chiller is active, and at certain nighttime hours, it operates at about 20-30% of its full capacity, leading to inefficient performance. Consequently, this study explores the potential of the CHWS to improve system efficiency and achieve economic benefits.

The chillers used in this study are centrifugal water-cooled types, with performance data at various loads provided in Appendix A1 (Trane, 2022). For Thailand, the performance curve chosen corresponds to an entering condenser water temperature (ECWT) of 85°F (29.4°C). The audited chilled water supply temperature ranges between 5.6°C and 7.2°C, with a temperature difference of approximately up to 7°C, and an entering condenser water temperature of 29.4°C. The indoor temperature is maintained between 23°C and 25°C, within the thermal comfort condition for Thailand (Department of Alternative Energy Development and Efficiency, Thailand, n.d.). Two cooling towers, each with a capacity of 1000 RT, are employed to cool the chiller condensers, and two 45 kW cooling water pumps (CWPs) with variable speed drives (VSD) circulating water between the units. Additionally, two 30 kW primary chilled water pumps (PCHWPs) and two 40 kW secondary chilled water pumps (SCHWPs) with VSD are used to circulate cooled water between the chillers and the load.

3. The Proposed CHWS-AC System

3.1 Chillers

Figures 3a-3c illustrate the schematic diagrams of the CHWS configurations for full storage (Full), partial load leveling (PLL), and partial demand limiting (PDL), designed to reduce electrical energy consumption and costs by taking advantage of lower electricity tariff rates and peak demand shifting. A stratified water storage tank, known for its simplicity, efficiency, and cost-effectiveness (Dorgan, & Elleson, 1993), is used in all three setups. According to the chiller performance curve in Appendix A1, the units run at 80% to 90% of full capacity, where power consumption per unit cooling (kW/RT) is at its lowest. In the full storage configuration, two existing chillers and an additional chiller, each with a capacity of 800 RT, operate at 90% capacity (720 RT) during off-peak hours to produce enough chilled water for the entire on-peak building load, with all chillers shutting down during on-peak hours.

In the partial load leveling design, the chiller must run continuously for 24 hours to meet the average cooling load of 900 RT, as shown in Figure 1. If two existing 800 RT chillers are used, one operating at 80% capacity (640 RT) would require the second chiller to run at 32.5% capacity (260 RT), leading to inefficient operation. To improve efficiency, a 260 RT unit running at full capacity (details provided in Appendix A2) is added to operate alongside the existing 800 RT chiller at 80% capacity, with the second 800 RT chiller kept on standby. This arrangement results in lower power consumption. In the partial demand limiting configuration, the two existing chillers operate at 80% capacity during off-peak hours, while only one chiller runs at 80% capacity during on-peak hours.

Charging of CHWS

Chilled water at an average of 5.6°C from the chillers flows in two directions: one part goes to the load (path 2-4) when there is a cooling demand, and the other part goes to the storage tank (path 2-3) for CHWS charging, as shown in Figures 3a-3c. Return water from the load coil at an average of 12.6°C (path 5) and warmer water from the upper part of the storage tank (paths 6-7, 6-8) flow back to the chillers to complete the charging loop. However, when the building load is low and the return temperature is significantly low, water will return to the coil via the bypass line (path 9-2-3-4).

Discharging of CHWS

During the discharge mode for full storage, all chillers and their associated pumps will shut off and the storage tank will directly provide all the necessary cooling (path 3-4). Only the SCHWPs with VSD will operate to meet the on-peak cooling demand. For partial storage, both the storage tank and the chillers will provide the necessary cooling.

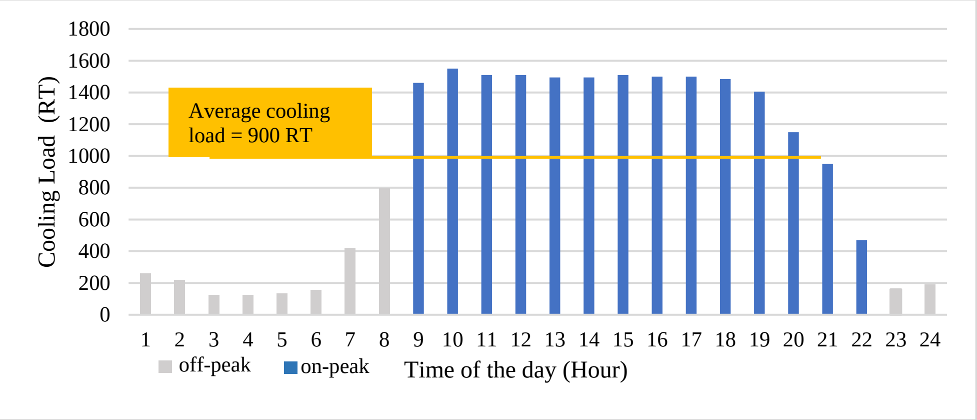

Figure 1 Hourly cooling load profile on a design day

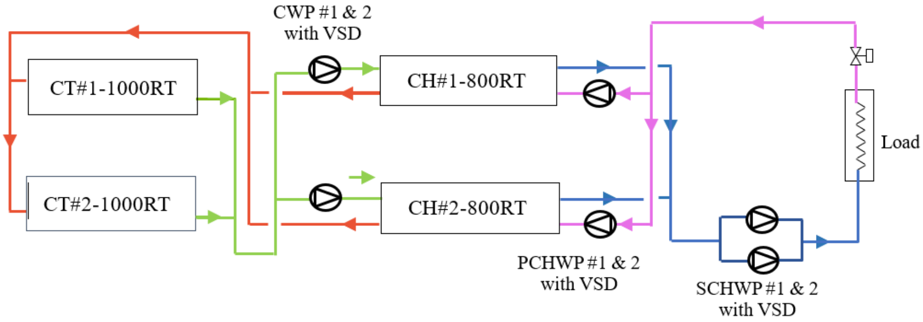

Figure 2 Schematic diagram of the existing chilled water system

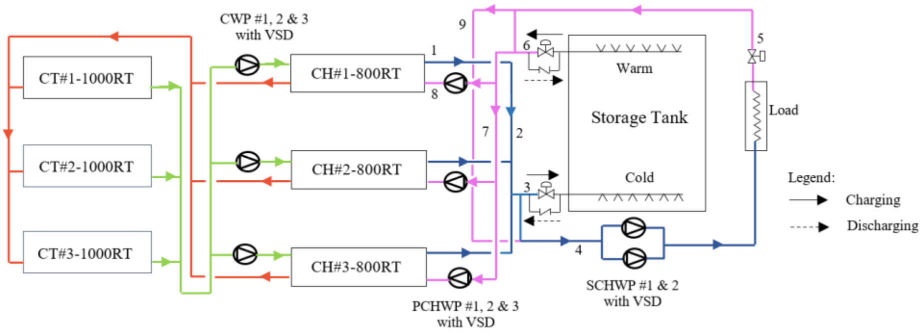

Figure 3a Schematic diagram of proposed CHWS AC system – Full Storage

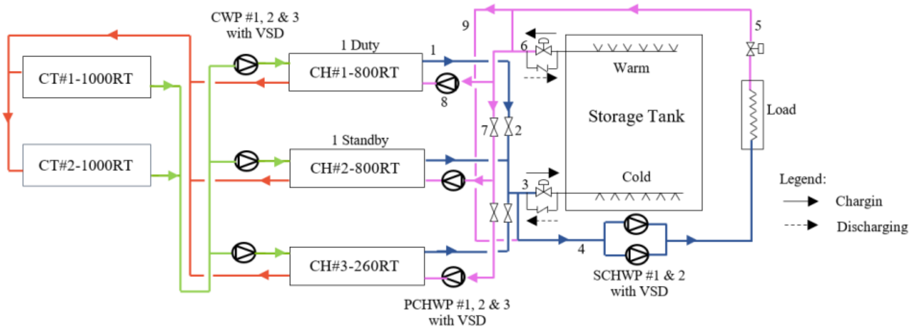

Figure 3b Schematic diagram of the proposed CHWS AC system – Partial Load Leveling

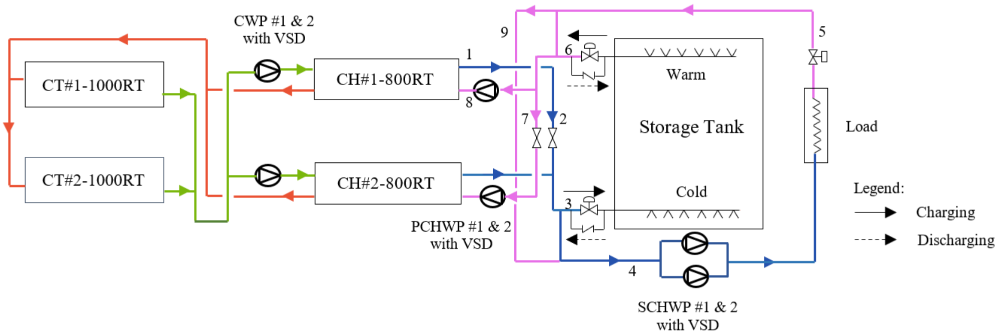

Figure 3c Schematic diagram of the proposed CHWS AC system – Partial Demand Limiting

3.2 Storage Tanks

The size of the cooled water storage tank can be estimated based on the daily storage capacity, which is determined by the difference between the cooling capacity produced by the chiller and the cooling load in each operating hour. The storage volume for each operating strategy can be determined from

$$V(theory)=\frac{3600\ x\ Daily\ Storage\ Capacity\ (kWh)}{\rho\ x\ C_{pw}\ x\ \ (T_{CHWR}\text{-}T_{CHWS})\ x\ \ FOM} \qquad (1)$$

V_{theory} is the volume of the storage tank (m^3), ρ is the density of water (kg/m^3), C_{pw} is the specific heat of water (kJ/kg °C), T_{CHWS} and T_{CHWR} are the inlet and outlet chilled water temperatures (°C) at the storage tank and the difference is 7°C in this study. FOM is the Figure of Merit which characterizes the performance of the CHWS by accounting for heat gain from the surroundings. (Dorgan, & Elleson, 1993) suggested that the FOM could range from 0.85 to 0.9. In this study, a value of 0.9 is used.

3.3 Chilled Water Pumps

3.3.1 Primary Chilled Water Pumps

The primary chilled water pumps are designed to circulate chilled water between the chillers and the storage tank. Their sizes are determined to offset the pressure drop in the chillers, storage tank, and piping losses within the circulation loop. A temperature differential of 7°C is maintained between the chilled water return (T_{CHWR}) and the chilled water supply (T_{CHWS}). The mass flow rate for the primary pumps can be calculated as

$$\dot{m}_{PCHWP}=\frac{RT_{chiller}\ x\ 3.52}{Cp_w\ \ x\ \ (T_{CHWR}\text{-}T_{CHWS})} \qquad (2)$$

The power requirement for the chilled water pumps at full load can be theoretically determined using the operating head of the primary loop, pump efficiency, and motor efficiency, which are 20 m, 85%, and 95%, respectively, as

$$P_{pump}=\frac{(\dot{m}_{PCHWP})(g)(h)}{10^3\ (\eta_p)(\eta_m)} \qquad (3)$$

Where, $RT_{chiller}$ is the ton of refrigeration, $\dot{m}_{PCHWP}$ is the mass flow rate (kg/s), g is the acceleration due to gravity (m/s^2), h is the operating head (m), η_p is the pump efficiency, η_m is the motor efficiency. The pump power at part load conditions is estimated by

$$P_{pump}@part\ load\ (kW)=P_{pump}\ @\ full\ load\ x\ PPR \qquad (4)$$

Where, PPR is the pump power ratio: $PPR=ax+bx^2+cx^3$, (California Energy Commission, 2013), which is a pump part-load power curve for pumps with variable speed control. x is the part load ratio of the pump at 90% and 80% part-load. a, b and c are constants: a = 0.0205, b = 0.4101, c = 0.5753.

3.3.2 Secondary Chilled Water Pumps

The secondary pumps circulate cooling water between the storage tank and the load. The flow rate through these pumps corresponds to the load's consumption capacity. The operating head for the secondary loop, and the pump and motor efficiency are defined as 28 m, 85%, and 95%, respectively. The mass flow rate for the secondary pumps can be calculated by

$$\dot{m}_{SCHWP}=\frac{RT_{load}\ x\ 3.52}{Cp_w\ \ x\ \ (T_{CHWR}\text{-}T_{CHWS})} \qquad (5)$$

The power requirement at the pump can be calculated from Eqs. (3, 4).

3.3.3 Cooling Water Pumps

Cooling water pumps with VSD are installed to circulate water between the chiller condenser and the cooling tower. The temperature difference between the cooling water return (T_{CWR})and the cooling water supply (T_{CWS}) at the cooling tower is 5.5 °C, with the operating head of the cooling water loop set at 25 m. The mass flow rate for the cooling water loop depends on the heat rejection requirements at the cooling tower and can be calculated by

$$\dot{m}_{CWP}=\frac{RT_{CT\_required}\,x\,3.52}{C_{pw}\,x\,(T_{CWR}\text{-}T_{CWS})} \tag{6}$$

The power requirement at the pump can also be calculated from Eqs. (3, 4). From the calculation, it is observed that the water pumps for the 800 RT chiller and cooling tower loop, as well as the 800 RT chiller and storage tank loop with load, do not exceed the full capacity of the existing pumps. Therefore, the CWPs, PCHWPs, and SCHWPs in the proposed systems will remain the same as those in the existing unit. For the PCHWP of the 260 RT chiller in the partial load leveling scenario, 25 kW capacity is suitable. All pump capacities for the proposed systems are detailed in Table 1.

3.3.4 Cooling Towers

The cooling tower sizes in the new system are similar to those in the existing system for rejecting heat from the chiller condenser. For full storage, three units of 1000 RT each are used, while for other scenarios, two units of 1000 RT each are employed. Each cooling tower is equipped with two 11.2 kW fan motors with VSD, and a motor efficiency of 92%, obtained from manufacturer’s catalogue. The cooling tower's power input at full load can be calculated by

$$P_{Fan}\;@\,full\;load=\left(\frac{Fan\;motor\;kW\;x\;nos.of\,fan}{\eta_m}\right)x\;\;nos.\;of\;CT, \tag{7}$$

and the cooling tower fan power input at part load is estimated by

$$P_{Fan}@part\;load\;(kW)=P_{Fan}\;@\,full\;load\;x\;FPR. \tag{8}$$

Where FPR is the fan power ratio: $FPR=a+bx+cx^2+dx^3$, (California Energy Commission, 2013), which is a cooling tower power adjustment curve with variable speed fan. x is the part load ratio of the cooling fan. a, b, c and d are constants: a=0.331629, b = -0.885676, c= 0.605565 and d= 0.948482. Part load ratio, x, can be calculated by

$$x=\frac{RT_{CT\_required}}{RT_{CT\_total}}x\;100\% \tag{9}$$

The selected sizes of the chillers, cooling towers and chilled water pumps of the proposed CHWS system are summarized in Table 1.

The whole system daily electrical energy consumption covers the power inputs at the chillers, primary and secondary pumps, cooling water pumps, and cooling towers during on-peak and off-peak periods and it could be evaluated by

$$\mathrm{P_{daily,chws}}=\textstyle\sum_{\text{on-peak}}\mathrm{P_{on\text{-}peak}}\cdot\mathrm{NOH}+\sum_{\text{off-peak}}\mathrm{P_{off\text{-}peak}}\cdot\mathrm{NOH} \tag{10}$$

Where, NOH is the number of operating hours during on-peak and off-peak periods.

The daily electrical energy savings (kWh/day) of the CHWS units compared to the existing unit can be calculated by

$$P_{savings}=P_{daily,\;existing}\text{-}P_{\;\;daily,chws} \tag{11}$$

4. Life Cycle Cost Analysis

The life cycle cost analysis covers the capital, electricity, maintenance costs, and salvage value over a 20-year period. Only the extra units of chillers, storage tanks, and cooling towers beyond the existing components are considered for capital costs. The required pump capacity of the proposed system does not exceed the full capacity of the existing pumps. Only one additional pump is required for full storage, but this additional cost is very low compared to those of the main equipment. Thus, the cost of the pump is neglected in this study. The initial cost of a chiller per capacity is estimated to be 300 US$/RT, according to Shaibani et al., (2019). The annual maintenance cost is estimated at 6.6 US$/RT/y, with a 2% increase per year. Detailed information on electrical tariffs, estimated prices for each component, discount rates, maintenance costs, and salvage values is provided in Table 2.

Table 1 The selected sizes of the chillers, cooling towers and chilled water pumps of the proposed CHWS system

Storage Options	**Chillers (RT)**	**PCHWP (kW)**	**SCHWP (kW)**	**CWP (kW)**	**CT (kW)**
Existing Unit	2x800	2x30	2x40	2x45	3x1000
Full	3x800 @90%	3x30	2x40	3x45	3x1000
PLL	2x800 @80% + 1x260	1x30+1x15	2x40	1x45+1x25	2x1000
PDL	2x800 @80%	2x30	2x40	2x45	2x1000

Table 2 Information data for life cycle cost analysis

Descriptions	**Quantity**	**Unit**
Electrical Tariff Rate (Metropolitan Electricity Authority, Thailand, 2023)		
Energy: On peak	0.12	US$/kWh
Energy: Off Peak	0.074	US$/kWh
Capital cost		
Chiller (Shaibani et al., 2019)	300	US$/RT
Tank cost (Van Asselt et al., 2017)	97 (Full)	US$/RT-h
	142 (PLL)	US$/RT-h
	122 (PDL)	US$/RT-h
Cooling Tower (Tawil, & Leed, 2001)	$982 \cdot RT_{CT}^{0.64}$	US$
Maintenance cost (Rismanchi et al., 2012) (2% increase/y)	6.6	US$/RT/y
Lifetime	20	years
Discount rate (Sullivan, 2024)	2	%
Salvage value	15	% of total capital cost

Electrical energy costs for each scenario are determined using Thailand's Time of Use (TOU) tariff rates. These rates are divided into on-peak periods (0.12 US$/kWh) from 9:00 a.m. to 10:00 p.m., and off-peak periods (0.074 US$/kWh) from 10:00 p.m. to 9:00 a.m. on working days. Off-peak periods also include weekends and public holidays. Approximately 245 days are accounted for with both rates, and 120 days solely for the off-peak rate.

The life cycle cost analyses for the systems cover calculations for the discounted payback period and internal rate of return (IRR), which are calculated as follows:

The payback period (PB) of the proposed system could be calculated by;

$$PB=(TIC+\text{Maintenance cost}-SV)/\text{Annual cost savings} \qquad (12)$$

The time value of money, with a 2% annual discount rate, is incorporated into all considered costs.

The internal rate of return (*IRR*) can be calculated by

$$\frac{\Sigma_{n=1}^{N} R_n - C_n}{(1+IRR)^N} - (TIC-SV)=0 \qquad (13)$$

Where R_n is the project revenue, which is the annual electrical energy saving in the nth year, C_n is the total expense cost which is annual maintenance cost in the nth year, TIC is the present total capital cost and SV is the present salvage value. The results are concluded in Table 6.

5. Results

5.1 Hourly Cooling Capacities of the Chillers with Three Proposed CHWS Configurations

The hourly generated cooling capacity profiles of the chillers with three proposed CHWS configurations compared to the contour of hourly cooling load are illustrated in Figure 4. For full storage, during the off-peak period from 10:00 p.m. to 9:00 a.m. on the next day, two 800 RT chillers, along with an additional 800 RT unit operating at 90% capacity, generate cooling for the required hourly cooling load and primarily for CHWS charging. This charged cooling capacity is sufficient to meet the total cooling load during the on-peak period from 9:00 a.m. to 10:00 p.m. During this period, all chillers, cooling towers, and associated pumps are switched off, and the cooling load is supplied directly by the storage tank. The total cooling capacity of the storage tank is 19,010 RTh, which can cover the building's daily on-peak cooling load.

For partial load leveling, one 800 RT chiller operates at 80% capacity while the other remains on standby. Along with a 260 RT unit running at full capacity, both chillers operate continuously for 24 hours to meet the average hourly cooling load of 900 RT. Excess cooling capacity generated beyond the cooling load each hour is stored in the storage tank for use during periods when the load demand exceeds the average. In this scenario, the calculated cooling capacity of the storage tank can be reduced to 6,840 RTh, which is sufficient to assist the chillers in supplying the daily cooling load during the on-peak period.

In the demand-limiting strategy, two 800 RT chillers are set to operate at 80% capacity during the off-peak period (10:00 p.m. to 9:00 a.m. on the next day), and only one unit runs at 80% capacity during the on-peak period (9:00 a.m. to 10:00 p.m.). The calculated cooling storage tank capacity of 10,380 RTh is sufficient to support these two chillers in meeting the daily cooling load during both on-peak and off-peak periods.

Table 3 shows the hourly generated cooling capacity of the chiller, cooling storage capacity and storage discharging capacity during on-peak and off-peak periods of the cooling system with three proposed CHWS compared with the existing unit. Additionally, the summation of the hourly cooling storage capacity allows calculating the required total cooling storage capacity.

Figure 5 shows the comparison of daily total electrical energy consumption for chillers with three CHWS configurations versus existing units. Only chillers, cooling towers, primary and secondary chilled water pumps, and cooling water pumps are considered in the system components analysis. It is evident that the main electrical energy consumption in all scenarios is at chillers. With the three CHWS configurations, each existing 800 RT chiller operates at optimal part load conditions (80-90% of full capacity), where power consumption per unit cooling (kW/RT) is minimized. As a result, these systems significantly reduce total electrical energy consumption compared to the existing units. The Partial Demand Limiting (PDL) design has the lowest energy consumption at 14.56 MWh/day, representing a 17% savings compared to the 17.56 MWh/day consumed by the existing system. The Full and Partial Load Leveling (PLL) configurations also show significant savings, consuming 14.98 and 15.41 MWh/day, respectively, for savings of 14.7% and 12.2%. These comparisons and savings are detailed in Table 4.

The annual electrical energy savings for three CHWS configurations compared to the existing setup are detailed in Table 5. The reduction in energy consumption not only results in cost savings but also benefits from the cost differential between on-peak and off-peak tariffs, leading to greater cost savings from the CHWS configurations than the electrical energy savings themselves. Calculations indicate that the Partial Demand Limiting (PDL) design results in the highest electrical energy savings among the CHWS configurations, followed by the Full and Partial Load Leveling (PLL) storage options. However, when considering annual cost savings, the Full storage configuration offers the highest savings because it mainly consumes electrical energy during the off-peak period, followed by the PDL and PLL configurations.

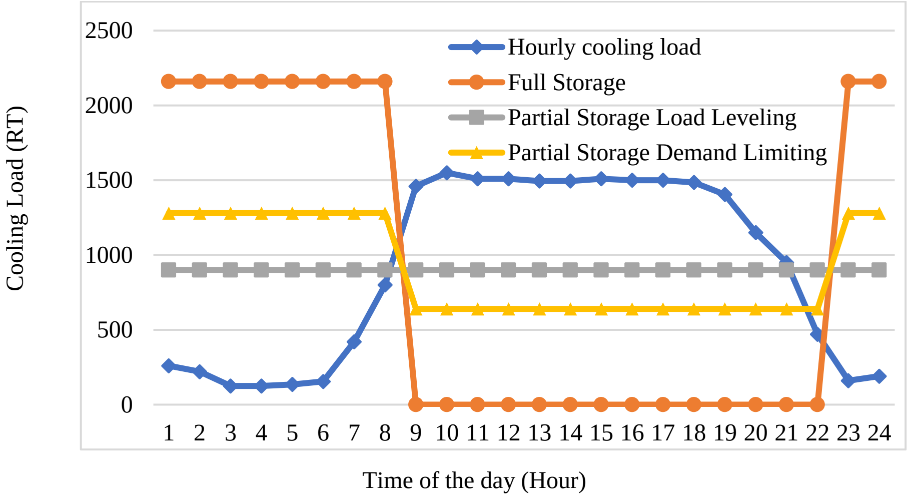

Figure 4 Profiles of hourly cooling capacities from three proposed CHWS configurations compared to the hourly cooling load

Table 3 Hourly load balance of chillers with three proposed CHWS

		Existing		**Full Storage**		**Partial Load Leveling**			**Partial Demand Limiting**		
Utility Period (O-clock)	**Load RT**	**Chillers in Operation RTh**	**Chillers in Operation RTh**	**Storage Capacity RTh**	**Storage Discharge RTh**	**Chillers in Operation RTh**	**Storage Capacity RTh**	**Storage Discharge RTh**	**Chillers in Operation RTh**	**Storage Capacity RTh**	**Storage Discharge RTh**
1-OP	260	1 x 260	3 x 720	1900	-	1x640 + 1x260	640		2 x 640	1020	
2-OP	220	1 x 220	3 x 720	1940	-	1x640 + 1x260	680		2 x 640	1060	
3-OP	125	1 x 125	3 x 720	2035	-	1x640 + 1x260	775		2 x 640	1155	
4-OP	125	1 x 125	3 x 720	2035	-	1x640 + 1x260	775		2 x 640	1155	
5-OP	135	1 x 135	3 x 720	2025	-	1x640 + 1x260	765		2 x 640	1145	
6-OP	155	1 x 155	3 x 720	2005	-	1x640 + 1x260	745		2 x 640	1125	
7-OP	420	1 x 420	3 x 720	1740	-	1x640 + 1x260	480		2 x 640	860	
8-OP	800	1 x 800	3 x 720	1360	-	1x640 + 1x260	100		2 x 640	480	
9-P	1460	2 x 730	off	0	1460	1x640 + 1x260		560	1 x 640		820
10-P	1550	2 x 775	off	0	1550	1x640 + 1x260		650	1 x 640		910
11-P	1510	2 x 755	off	0	1510	1x640 + 1x260		610	1 x 640		870
12-P	1510	2 x 755	off	0	1510	1x640 + 1x260		610	1 x 640		870
13-P	1495	2 x 748	off	0	1495	1x640 + 1x260		595	1 x 640		855
14-P	1495	2 x 748	off	0	1495	1x640 + 1x260		595	1 x 640		855
15-P	1510	2 x 755	off	0	1510	1x640 + 1x260		610	1 x 640		870
16-P	1500	2 x 750	off	0	1500	1x640 + 1x260		600	1 x 640		860
17-P	1500	2 x 750	off	0	1500	1x640 + 1x260		600	1 x 640		860
18-P	1485	2 x 743	off	0	1485	1x640 + 1x260		585	1 x 640		845
19-P	1400	2 x 700	off	0	1400	1x640 + 1x260		500	1 x 640		760
20-P	1150	2 x 575	off	0	1150	1x640 + 1x260		250	1 x 640		510

Table 3 Cont.

Utility Period (O-clock)	Load RT	Existing		Full Storage		Partial Load Leveling			Partial Demand Limiting		
		Chillers in Operation RTh	**Chillers in Operation RTh**	**Storage Capacity RTh**	**Storage Discharge RTh**	**Chillers in Operation RTh**	**Storage Capacity RTh**	**Chillers in Operation RTh**	**Chillers in Operation RTh**	**Storage Capacity RTh**	**Storage Discharge RTh**
21-P	950	2 x 475	off	0	950	1x640 + 1x260		50	1 x 640		310
22-P	470	1 x 470	off	0	470	1x640 + 1x260	430		1 x 640	170	
23-OP	160	1 x 160	3 x 720	2000	-	1x640 + 1x260	740		2 x 640	1120	
24-OP	190	1 x 190	3 x 720	1970	-	1x640 + 1x260	710		2 x 640	1090	
Total	21585			19010	18985		6840	6815		10380	10195

**Note: Loads and cooling capacities are shown in refrigeration ton (RT), which can be converted to kW as 1 RT = 3.52 kW. OP refers to off-peak and P refers to on-peak.

Table 4 Daily electrical energy consumption and saving

Description	Existing Unit	Full Storage	Partial Load Leveling	Partial Demand Limiting
On-peak (kWh)	15331	775	9315	6452
Off-peak (kWh)	2225	14200	6100	8110
Total electrical energy (kWh)	17555	14975	15415	14562
Electrical energy saving (kWh)		2580 (14.7%)	2140 (12.2%)	2993 (17%)

Table 5 Annual cost of electrical energy savings

Description	Existing Unit	Full	Partial Load Leveling	Partial Demand Limiting
Daily electrical energy (kWh)	17555	14975	15415	14562
Daily electrical energy saving (kWh)		2580 (14.7 %)	2140 (12.2%)	2993 (17%)
Annual cost (US$)	646,968	413,209	521,339	466,034
Annual cost savings (US$)		233,759 (36.3%)	125,629 (19.4%)	180,934 (27.9%)

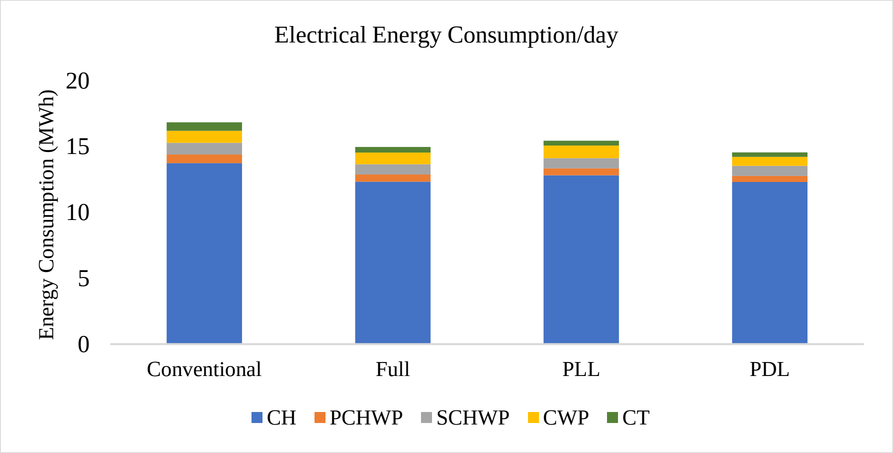

Figure 5 Comparison of daily electrical energy consumption of chillers with three CHWS configurations versus existing units

Table 6 Summary of Result of Economic Analysis

Description	Full Storage	Partial Load Leveling	50% Demand Limiting
Chiller capacity (RT)	3x800 @ 90%	1x800 @ 80% + 1x260	2x800 @ 80% (off-peak) 1x800 @ 80% (On-peak)
Storage tank (m^3)	9,150	3,292	4,987
Chiller (US$)	240,000 (for 1 extra 800 RT)	78,000 (for 1 extra 260 RT)	-
Tank cost (US$)	1,843,000	969,860	1,265,140
Cooling Tower (US$)	81,679	-	-
Total capital cost (US$)	2,164,679	1,047,860	1,265,140
Annual maintenance cost (US$/y)	15,529	6,859	10,353
Annual cost savings (US$/y)	233,759	125,629	180,934
Total profit (US$/y)	217,919	118,770	170,374
Payback period (y)	9.65	8.6	7.42
IRR (%)	10.33%	12.08%	14.92%

5.2 Economic Analysis

After calculating energy savings, cost savings, payback period, and IRR, the summary of the results of the economic analysis is tabulated in Table 6.

According to Table 6, while the Full storage configuration achieves the highest annual electrical energy savings, it also incurs the greatest total capital cost due to additional investments in an extra chiller and cooling tower, along with a larger storage tank. Consequently, this configuration has the longest payback period of 9.65 years and the lowest IRR at 10.33%. In contrast, the PDL configuration is identified as the most advantageous system. It utilizes the existing cooling system dimensions and a smaller storage tank, yielding the shortest payback period of 7.42 years and the highest IRR at 14.92%. This is followed by the PLL configuration, which has a payback period of 8.6 years and an IRR of 12.08%.

6. Conclusions

This study investigates the technical implementation of Chilled Water Storage (CHWS) systems with three operational strategies: full storage, partial load leveling (PLL), and partial demand limiting (PDL), integrated into the existing air conditioning system of a retail mall. In the current system, the chiller sometimes runs at a low percentage of its full capacity, reducing energy performance and increasing energy consumption. With the implementation of CHWS technology, the chiller can operate under optimal conditions, lowering energy usage. Moreover, peak demand during on-peak periods can be further reduced through load shifting strategies. The research also evaluates the economic benefits of these strategies by analyzing electricity tariffs during peak and off-peak periods to determine the appropriate chilled water storage capacities. The findings of this study can be summarized as follows:

- Compared to the existing setup, which operates two 800 RT chillers continuously during on-peak hours and one chiller at 20-30% capacity during off-peak hours, the proposed strategies include three 800 RT chillers with a 9,150 m^3 tank for full storage, one 800 RT and one 260 RT chiller with a 3,292 m^3 tank for partial load leveling, and two 800 RT chillers with a 4,987 m^3 tank for partial demand limiting, offer significant reductions in electrical energy consumption.
- All strategies notably decreased electrical energy consumption compared to the existing setup, which uses 17.56 MWh/day. The partial demand limiting (PDL) strategy was the most effective, reducing energy consumption to 14.56 MWh/day (17% savings). The full storage and partial load leveling (PLL) strategies also performed workably with energy reductions of 14.98 MWh/day (14.7% savings) and 15.41 MWh/day (12.2% savings), respectively. But in terms of annual electrical cost savings, the Full Storage configuration showed the highest savings at 36.3%, due to its extensive use of lower cost energy during off-peak hours. The PDL and PLL strategies provided annual cost savings of 27.9% and 19.4%, respectively. Despite its higher electrical energy cost savings, the Full Storage strategy involved the highest initial investment, leading to the longest payback period of 9.65 years and the lowest internal rate of return (IRR) at 10.33%. Conversely, the PDL strategy proved to be the most economically viable, with the shortest payback period of 7.42 years and the highest IRR at 14.92%, making it the most beneficial strategy for implementation.

The limitation of a CHWS system with water as the working medium is that energy is stored as sensible heat, which requires large and expensive storage tanks. To reduce the tank size, ice or ice slurry, which stores energy as latent heat, is often employed. However, this forces the chiller to operate at lower temperatures, reducing thermal performance and increasing electrical energy consumption. A promising solution for future work is to integrate phase change materials (PCMs) into the CHWS. PCMs store energy as latent heat, and their melting point should be optimized to around 5-7°C, allowing the chiller to maintain high performance while reducing the size of the storage tank.

7. Nomenclature

CH – Chiller
CT – Cooling tower
PCHWP – Primary chilled water pump
SCHWP – Secondary chilled water pump

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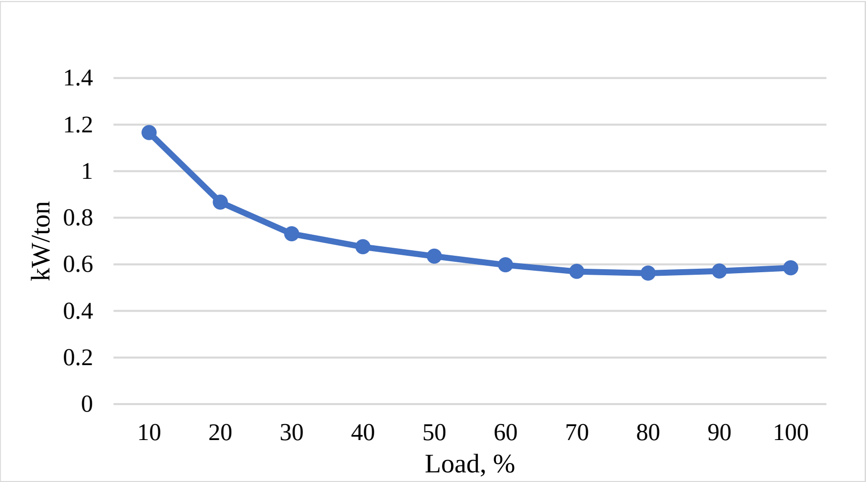
Appendix A

A1 Performance curve of 800 ton (2800 kW) centrifugal water-cooled chiller (Trane, 2022)



Chiller with a unit-mounted variable speed drive designed at evaporator: 5.6°C /12.8°C, condenser: 29.4°C and flow 2.5 gpm/ton

Figure A1 Power Consumption (kW) per unit ton of refrigerant (kW/ton) with percent cooling load.

A2 Technical data for 260 RT water-cooled chiller (Hitachi, 2024)

Table A2 260 RT water-cooled chiller

WZY Series		
Cooling capacity	kW	915
	RT	260
Power input (kW)		163.7
Compressor quantity		1
Chilled water in/out (°C)		7/12.2
Chilled water flow (m^3/hr)		157.4
Chilled-water pressure drop (kPa)		34
Condenser water in/out (°C)		30/35
Condenser water flow (m^3/hr)		196.7
Condenser pressure drop (kPa)		82