

Original Article

An Approach to Managing Chillers for Air Conditioning Systems in Shopping Malls in Thailand

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Abstract - The effective management of air conditioning systems is imperative for achieving carbon neutrality in large-scale shopping malls, as these systems are responsible for approximately 60–80% of overall electricity consumption. This study investigates three shopping malls in Thailand as case studies, employing reference data obtained from the mandatory implementation of the Thai Building Energy Code (BEC). The external climatic conditions of the investigated area can be represented by a maximum average dry-bulb temperature of 33 °C and a maximum average wet-bulb temperature of 27 °C. The three shopping malls contain gross floor areas varying from 25,000 to 50,000 m². The results reveal that Shopping Mall B exhibits greater potential for gaining carbon neutrality in its air conditioning refrigeration systems with respect to Shopping Malls A and C, mainly caused by its lower energy consumption per unit floor area. The annual electricity consumption of Shopping Mall B is 10,946,225.52 kWh, resulting in carbon dioxide emissions of 5,472.02 tCO₂-eq/year. These findings indicate that using solar Photovoltaic (PV) systems for daytime electricity production is an effective mitigation strategy. The introduction of a minimum PV capacity of 4 MW significantly reduces carbon dioxide equivalent emissions by approximately 54.81%. Thus, the suggested integrated approach proposes an important significant possibility for lowering carbon dioxide equivalent emissions in large-scale shopping malls.

Keywords - Cooling load, Chiller, Shopping mall, Carbon neutrality, Energy efficiency.

1. Introduction

Shopping malls typically use centralized, water-cooled chilled-water systems for air conditioning. Basically, chillers are used in these systems to provide chilled water for area cooling. The chilled water supply temperature is technically set up at the range of 44–45 °F, and the chilled water return temperature (CHR) normally varies from 54–55 °F with a flow rate of 2.4 GPM/TR. The condenser water temperature leaving the chiller is often around 100 °F, while the entering condenser water temperature is normally 90 °F. The chilled water flows through cooling coils, where blowers accelerate air across the coils to promote heat transfer and dehumidification. The air temperature is therefore decreased to the appropriate range and then delivered to air-conditioned areas in the shopping mall. Central air-conditioning systems are basically responsible for approximately 60–80% of the total electricity consumption in shopping mall buildings [1]. Hence, the efficient operation and management of air-conditioning equipment are of great significance. Technically, common practices such as decreasing operating hours reduction, adjusting temperature setpoints, and performing routine maintenance can reduce energy consumption by

approximately 5-10%. Furthermore, the addition of energy-saving equipment, the use of automated control systems, and appropriate structure design can promote a further reduction of 15-30% in air-conditioning energy consumption [2]. In contrast, ineffective air-conditioning system operations in shopping malls raise energy costs and negatively affect system maintenance. Therefore, the energy consumption and operational cost of air-conditioning systems are considered as primary factors in establishing suitable cooling system designs for shopping mall buildings, indicating that efficient energy reduction approaches are clearly required in major building systems.

Similarly, the trend toward carbon neutrality aims to regulate carbon dioxide emissions and removals to achieve net-zero emissions [3, 4]. Several carbon reduction approaches, including promoting the use of renewable energy and reducing the consumption of fossil fuels, are conducted to decrease emissions at the source. In addition, carbon compensation strategies, such as reforestation and development in low-carbon projects, can be employed to support these efforts.



Clearly, collaboration from many industrial sections is required to achieve carbon neutrality. For chilled-water systems in this can be achieved by using high-efficiency chillers, employing improved operational management for optimizing cooling production in response to the building cooling demand, and applying appropriate maintenance activities. Recently, innovative approaches including the addition of renewable energy sources, the use of intelligent technologies such as Artificial Intelligence (AI) and the Internet of Things (IoT), predictive maintenance based on real-time monitoring and data analytics, the selection of green refrigerants and the improvements in total energy management to reduce electricity consumption from the main grid, have played an imperative role in cost saving and greenhouse gas emission reduction [5-8]. However, the practical application and performance assessment of these integrated approaches in large-scale shopping mall air-conditioning systems under actual operating conditions are still limited. In fact, most previous investigations have focused on specific chiller technologies and simulation methods, but less work has been done for the comprehensive evaluation of actual chiller operation under real operating conditions, particularly in large shopping malls. Moreover, limited attention has been given to the investigation of cooling-load characteristics, energy performance (kW/TR), electricity consumption, greenhouse gas emissions, and economic feasibility using measured operational data.

To address this gap, this study evaluates actual cooling load characteristics over a one-year period and compares them with calculated electricity consumption from air-conditioning systems in three shopping mall case studies in Thailand using measured operational data collected under actual operating conditions. The shopping malls differ in size, with gross floor areas between 25,000 and 50,000 m². One aim of the present investigation is to determine the effectiveness of current air-conditioning systems in terms of energy efficiency and carbon dioxide equivalent emissions. The other aim is to propose effective energy management strategies and develop an integrated approach for air-conditioning system management in large-scale shopping malls in Thailand to support the transition toward carbon neutrality.

2. Methodology

2.1. Building Characteristics and Energy-Related Parameters

This investigation utilized three shopping mall buildings as case studies: one mall in Bangkok and two malls in the provincial areas of Thailand. The evaluation was conducted based on the required Thai Building Energy Code (BEC). The study locations are characterized by a maximum average dry-bulb temperature of 33 °C and a maximum average wet-bulb temperature of 27 °C [3].

The three shopping malls have total floor areas ranging from 25,000 to 50,000 m². More than 60 % of the gross floor

areas in each shopping mall are air-conditioned. The overall heat transfer coefficient of the building envelope is influenced by several parameters, including construction material thickness and material properties. According to architectural specifications, the shading coefficient of the glazing used in the shopping malls is 0.66 [2]. The energy performance parameters of the building envelope and lighting systems in accordance with Thai building energy efficiency standards are summarized in Table 1. In addition, Table 2 shows the hourly occupancy rates, lighting loads, and electrical equipment loads used in the analysis.

Table 1. Energy efficiency standards for building envelope systems [9]

Description	Thai Standard Conditions (12 Hours of Operation)	The Investigated Building
Overall Thermal Transfer Value (OTTV)	$\leq 40 \text{ W/m}^2$	32.4 W/m ²
Roof Thermal Transfer Value (RTTV)	$\leq 8 \text{ W/m}^2$	4.7 W/m ²
Lighting Power Density (LPD)	$\leq 11 \text{ W/m}^2$	8.5 W/m ²

Table 2. Occupancy, lighting, and equipment loads

Description	Hour	Percentage (%)
People	00:00-09:00	0
	09:00-10:00	10
	11:00-13:00	40
	13:00-15:00	60
	15:00-17:00	60
	17:00-20:00	100
	20:00-22:00	10
	22:00-00:00	0
Lights	00:00-09:00	0
	09:00-10:00	50
	10:00-21:00	100
	21:00-22:00	20
	22:00-00:00	0
Equipment	00:00-09:00	0
	09:00-10:00	10
	10:00-11:00	40
	11:00-16:00	100
	16:00-21:00	60
	21:00-22:00	10
	22:00-00:00	0

2.2. Data Collection and Performance Evaluation

In this study, data regarding cooling loads and electricity consumption of the air-conditioning systems were obtained from the three shopping mall buildings. The air-conditioning systems are equipped with a computerized data acquisition system, which allows for automatic data logging during system operation. The data set used in this study is from the

year 2024. The measured parameters are chilled water temperatures, condenser water temperatures, chiller pump pressures, chilled water flow rates, and cooling tower water flow rates. These parameters were used to estimate the cooling load and energy consumption of the air-conditioning system.

In addition, refrigerant-related data and other relevant operational variables were gathered [10-13]. The specifications of the chillers examined in this study are presented in Table 3.

Table 3. Cooling capacity specifications of the three shopping mall buildings

Shopping Mall	Air-conditioned Area (m ²)	Location	Cooling Capacity (TR)	Compressor Type	Refrigerant Type
A	26,271	Kanchanaburi	1,960	Centrifugal	R134a
B	35,059	Saraburi	2,000	Centrifugal	R134a
C	45,709	Bangkok	2,800	Centrifugal	R123

Shopping Malls A and B are full-service shopping centers designed to users of all ages. These malls combine shop space, food and beverage areas, and recreational facilities. In addition, they also support local economic activities. Conversely, Shopping Mall C is the second shopping mall within the EM District development, and it consists of a cinema complex and office buildings.

The performance assessment of the centralized air-conditioning systems in the three shopping malls focuses on the operational efficiency of the chilled-water systems. Cooling load data recorded by the operating company were utilized to evaluate the performance of the central air-conditioning systems. The system performance was assessed using the ratio of electrical power consumption to cooling capacity, defined as kilowatts per ton of refrigeration (kW/TR) [6, 14-16].

The performance parameters were computed by applying Equations (1) and (2). The kW/TR index is generally used as a performance evaluation index for large centralised water-cooled chiller systems and is consistent with the performance standards defined in ASHRAE Standard 90.1[17-19]. It was therefore selected as the main performance indicator of this study.

$$\text{Chp} = \text{PC} / \text{Q} \quad (1)$$

$$\text{PC} = \text{Power consumption (kW)}$$

$$\text{Q} = \text{Cooling capacity (TR)}$$

$$\text{Q} = \text{F} \times \Delta\text{T} / 24 \quad (2)$$

$$\text{F} = \text{Chilled water flow rate (GPM)}$$

$$\Delta\text{T} = \text{Chilled water temperature difference (°F)}$$

The performance evaluation of centralized air-conditioning systems involves recording the cooling load profiles of shopping mall buildings to analyze the operational performance of the systems. The ratio of electrical power consumption to cooling capacity, calculated in kilowatts per ton of refrigeration (kW/TR), is used to indicate system performance [20-22]. Maximum performance of a chiller can

be evaluated when it operates within its highest efficiency range [23, 24]. This normally occurs when the chiller is working at 80–95% of its cooling load [25, 26]. As a result, the current limit should be fixed to be less than 95% because this operating situation generates a lower kW/TR value.

2.3. Measuring a Carbon Footprint using the GHG Protocol and ISO 14064:2006

Carbon footprint's quantity can be determined using both the ISO 14064-1:2006 standard and the (GHG) Protocol, which are used globally by organizations to measure and verify their carbon footprints. The GHG Protocol is a joint initiative of World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD). The ISO 14064-1:2006 standard determines regulations and guidelines for organizations to quantify and report their Greenhouse Gas (GHG) emissions and removals [27]. It also sets requirements for the design, development, management, reporting, and verification of an organization's GHG inventory.

3. Experimental System and Measurement Procedure

The measurement instruments and performance evaluation in this study were then applied to centralized air-conditioning systems employing magnetic bearing, water-cooled chillers. The system contains four water-cooled magnetic bearing chillers, each of which has a cooling capacity of 1,000 tons of refrigeration. In fact, magnetic bearing chillers use magnetic bearing technology in the compressor. With this technique, the shaft can function without physical contact. As a result, this kind of chiller exhibits reduced friction, increased energy efficiency, and eliminates the need for lubrication oil. So, maintenance requirements are reduced, and the service life of the equipment become extended. The performance evaluation was carried out under normal operating conditions during the measurement period. Table 4 provides a summary of the detailed procedures and operating conditions used for the chiller performance measurements.

Table 4. Shows the method of measuring for central air conditioning

Sequence No.	Measurement	Measuring instruments	Characteristics of measurement
1	Cool water flow measurement	Ultrasonic Flow meter	To perform a temporary measurement with continuous recording every 15 minutes for 7days
2	Measure the temperature of cool water inlet and outlet	Thermometer	
3	Electrical power measurement	Power meter	

To validate the reliability of the recorded data, all measurements were conducted using calibrated measuring instruments with specified measurement accuracies under normal operating conditions during the measurement period. The measurement accuracy of each instrument is described below. In this investigation, an ultrasonic flow meter (Micronics Porta Flow MF220B) was used to measure the flow rate of the chilled water. The measurement accuracy of the flow meter varies from $\pm 0.5\%$ to $\pm 2\%$ of the reading for flow velocities greater than 0.2 m/s with pipe Inner Diameters (ID) greater than 75 mm, $\pm 3\%$ of the reading for flow velocities greater than 0.2 m/s with IDs ranging from 13 to 75 mm, and $\pm 6\%$ of the reading for flow velocities less than 0.2 m/s. The inlet and outlet temperatures of the chilled water were obtained using a thermometer (LUTRON, model TM-1947SD, Type K). This thermometer can be used in a temperature range of $-50.0\text{ }^{\circ}\text{C}$ to $999.9\text{ }^{\circ}\text{C}$ and an accuracy of $\pm(0.4\% + 1\text{ }^{\circ}\text{C})$ with an accuracy of $\pm(0.4\% + 1\text{ }^{\circ}\text{C})$. A power meter with a continuous data recorder was employed to measure electrical power consumption. This device can measure voltages ranging from 2 V to 1,000 V and currents from 0.1 A to 10,000 A, with an accuracy of $\pm 5\%$ of the nominal voltage and $\pm(5\% + 5\text{ counts})$. Based on the performance evaluation of the centralized water-cooled air-conditioning systems in the three shopping mall buildings, the measured performance results are presented and discussed in the following section.

4. Result and discussions

4.1. Performance Assessment of Chiller Systems in the Three Shopping Malls

Figure 1 exhibits the cooling performance of the centralized air-conditioning systems (kW/TR) for the three shopping malls during the working period from 09:30 to 21:30. For Shopping Mall A, the average measured electrical power consumption was 994.56 kW. This power consumption consisted of 707.30 kW for the chillers, 127.33 kW for the chilled water pumps, 128.34 kW for the condenser water pumps, and 31.59 kW for the cooling towers.

The average cooling load was 910.03 TR, equivalent to an average operating load of 61.91%, and an average system performance was 0.777 kW/TR. In case of Shopping Mall B, the average electrical power consumption was 986.18 kW. This value of power consumption included 737.83 kW for the chillers, 102.33 kW for the chilled water pumps, 103.59 kW for the condenser water pumps, and 42.43 kW for the cooling towers. The average cooling load was 961.67 TR, corresponding to an average operating load of 78.49%. Therefore, the average system performance was 0.767 kW/TR, which is the lowest among the three shopping malls. For Shopping Mall C, the average measured electrical power consumption was 950.91 kW.

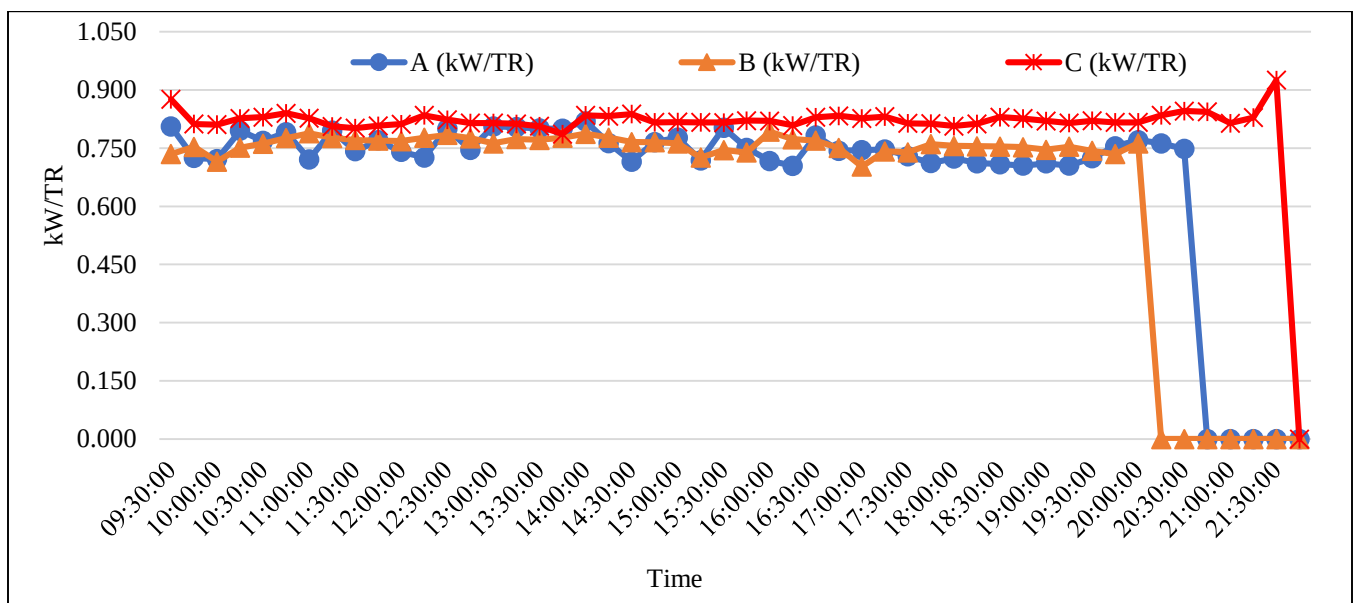


Fig. 1 Energy efficiency performance of the chiller (kW/TR)

This power consumption is composed of 718.34 kW for the chillers, 109.80 kW for the chilled water pumps, 82.59 kW for the condenser water pumps, and 40.18 kW for the cooling towers. The average cooling load was 878.90 TR, in line with an average operating load of 62.96%. The average system performance was then 0.817 kW/TR. A comparison of the

three shopping malls indicates that the cooling load profiles differ significantly. This is because each mall has different operational characteristics and the size of air-conditioned areas. These variations in cooling demands are shown in Figure 2.

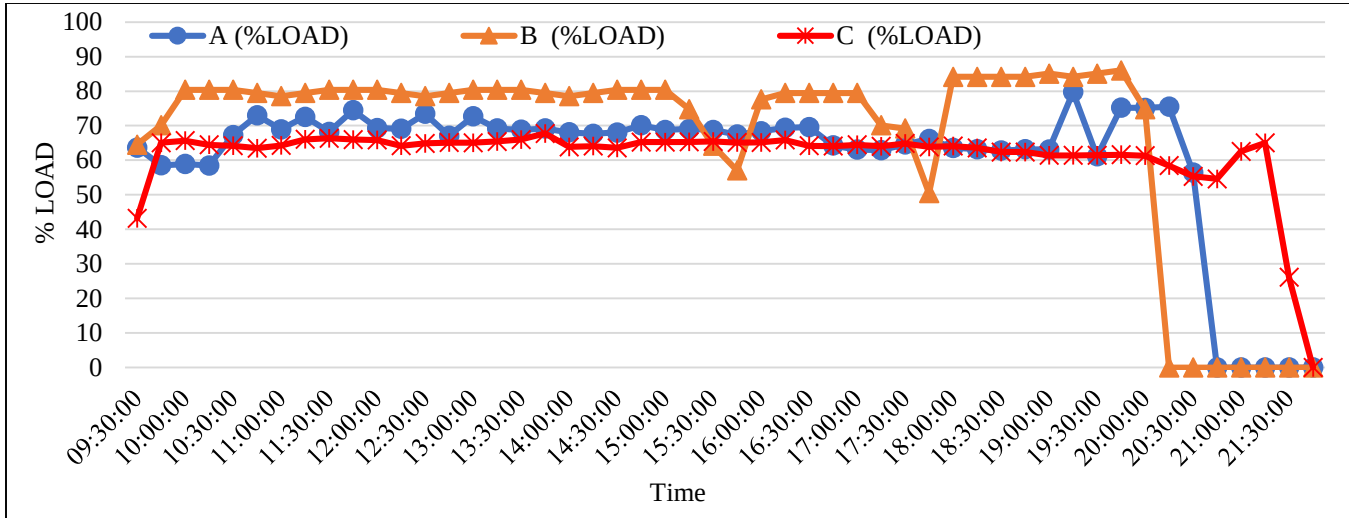


Fig. 2 Cooling load variation of the three shopping malls

The cooling demand variation of the three shopping malls is presented in Figure 2. The results show that the cooling load of Shopping Mall A is continuously stable from 10:30 to 19:15, with an average cooling load of 60.77%. Similarly, Shopping Mall B shows a relatively stable cooling load from 10:00 to 15:00, with an average cooling load of 66.90%. Shopping Mall C shows a stable cooling load throughout a longer operating period, from 09:45 to 20:00, with an average

cooling load of 61.38%, with an average cooling load of 61.38%. Clearly, the analysis suggests that the lower cooling load observed in a shopping mall contributes to its functional characteristics, especially the presence of a cinema complex and office spaces. A comparison between floor area utilization and cooling demand for the three shopping malls is provided in Figure 3.

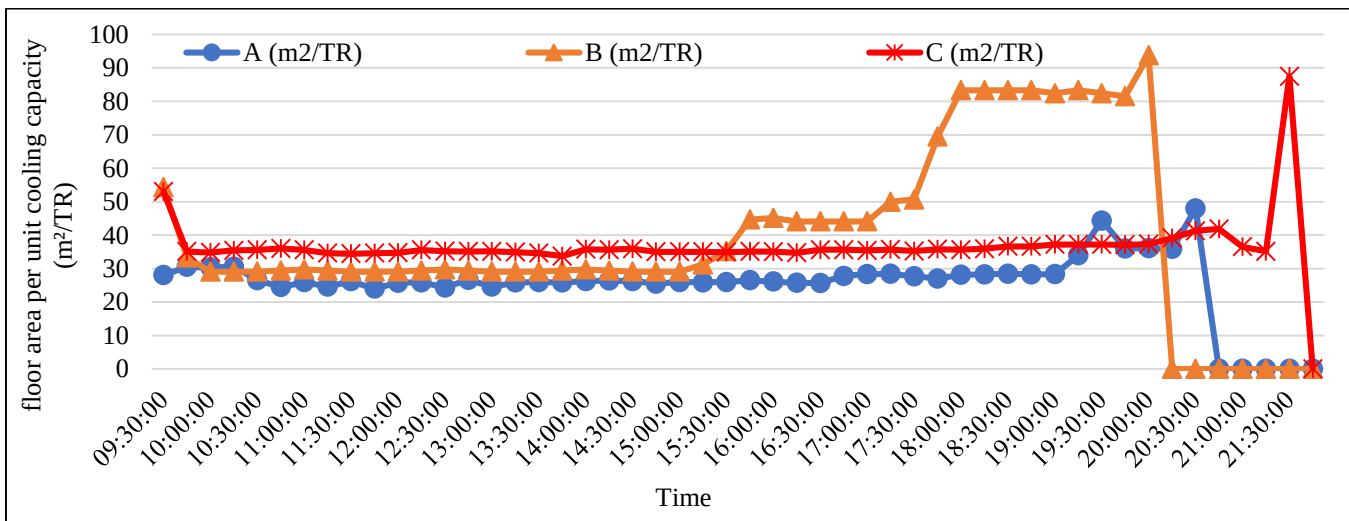


Fig. 3 Comparison of floor area per unit cooling capacity (m²/TR)

The comparison of the floor area per unit cooling capacity (m²/TR) of the three shopping malls is illustrated in Figure 3.

The results clearly indicate that Shopping Mall B exhibits a more suitable air-conditioning system management strategy in

comparison to the other two shopping malls. This shopping mall uses a centralized water-cooled chiller system consisting of four chillers, each of which possesses a cooling capacity of 500 TR ($\text{CH}_2\text{--CH}_4$), together with supplementary equipment such as chilled water pumps, condenser water pumps, and cooling towers. Regarding operation, three chillers are operated daily starting at 09:30, with shutdown times at 17:00, 20:00, and 21:00, respectively. The chilled water pumps are operated based on the number of active chillers and are equipped with Variable Speed Drives (VSDs), with the operation frequency set at 42 Hz. Likewise, the condenser

water pumps are operated corresponding to chiller operation, and they are equipped with variable speed drives operating at 50 Hz. All cooling towers are operated at the same time, and they are shut down with the chillers. The cooling tower fans are also equipped with variable speed drives which operate at a frequency of 45 Hz. In comparison to the other two shopping malls, this coordinated operation strategy achieves a higher air-conditioned floor area per ton of refrigeration, indicating more efficient cooling system management. Figure 4 shows the comparison of cooling load of the three shopping malls.

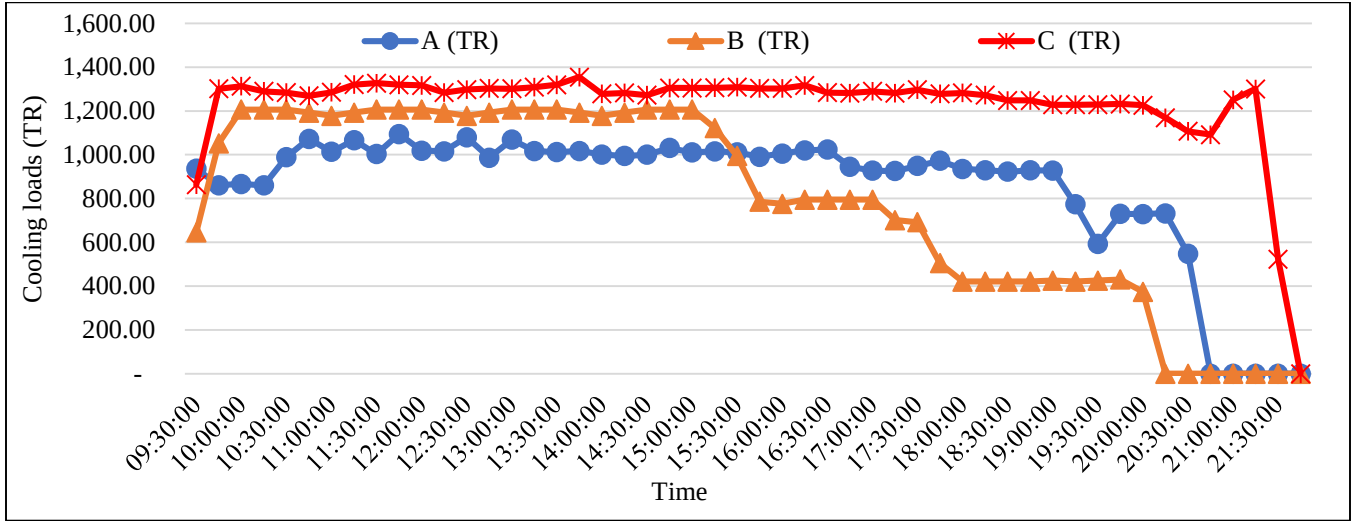


Fig. 4 Comparison of cooling loads of the three shopping malls

Figure 4 illustrates the comparison of cooling loads of the three shopping malls. The results demonstrate that Shopping Mall B reduces its cooling capacity by shutting down one chiller at 15:00 and another at 17:00 and then shutting down all chillers at 20:00. Evidently, this operating strategy does not affect occupant comfort or shopping activities. Conversely,

Shopping Malls A and C maintain their chillers at steady levels during the whole business hours. A comparison of monthly electricity consumption of the air-conditioning systems normalized by air-conditioned floor area is provided in Figure 5.

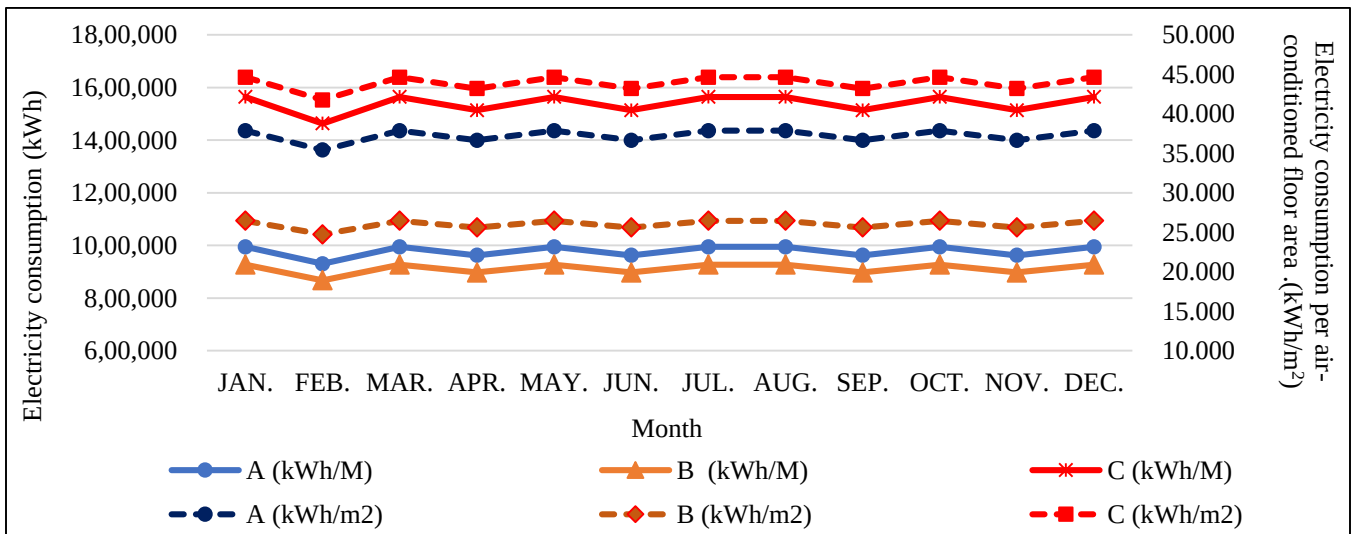


Fig. 5 Comparison of monthly electricity consumption of the air-conditioning systems per air-conditioned floor area

The monthly electricity consumption of the air-conditioning systems is compared in Figure 5, which is normalized by the air-conditioned floor area. The results clearly indicate that Shopping Mall C exhibits the highest monthly electricity consumption for cooling in each month, followed by Shopping Malls A and B, respectively. As electricity consumption is evaluated on a per-unit-area basis, Shopping Mall B demonstrates the lowest energy use, with an average value of 26.02 kWh/m² per month. This is followed by Shopping Mall A, with an average consumption of 37.25 kWh/m² per month, and Shopping Mall C, which records the highest average value of 43.90 kWh/m² per month. Thus, Shopping Mall C has the highest greenhouse gas emissions related to electricity consumption for air-conditioning cooling among the three shopping malls.

4.2. Comparative Analysis of Chiller Technologies

The selection of a suitable chiller technology is crucial to improving the energy efficiency of air-conditioning systems in commercial buildings in Thailand. Principally, two basic types of chillers are widely used for large scale air-conditioning applications; air-cooled chillers and water cooled chillers. The electrical power consumption per unit cooling capacity (kW/TR), regarded as the main indicator of chiller energy efficiency, is generally employed to evaluate the performance of chillers. In addition, the application of minimum energy performance standards not only provides practical advice for the selection of suitable chiller system for commercial buildings but also facilitates energy conservation consistent with as specified by national energy efficiency objectives [6-8].

The energy performance of chillers used in Thailand is normally evaluated based on two standard operating conditions. On one hand, the first requirement is to evaluate the chiller performance at full-load conditions for both air-cooled and water-cooled chillers. On the other hand, the second factor considers the efficiency at full load and part load using the Integrated Part Load Value (IPLV) and Non-

Standard Part Load Value (NPLV). This method effectively reflects the actual operating conditions of the system. This is because most commercial buildings rarely operate constantly at full load. Thus, assessing chiller performance with the consideration of part-load conditions can present a more realistic foundation for evaluating the total energy efficiency of chiller system.

In Thailand, the air conditioning system in commercial buildings is responsible for about 60 – 80% of the total electricity. Therefore, inadequate chiller performance or improper control approach can lead to large energy losses and increased operational costs. For water-cooled chillers, standard design requirements include a chilled-water supply temperature (CHS) of 44–45 °F, a chilled-water return temperature (CHR) of 54–55 °F, a chilled-water flow rate of 2.4 GPM/TR, and a condenser-water flow rate of 3.0 GPM/TR. The condenser water exit and entry temperatures are typically set up at 100 °F and 90 °F, respectively. Typically, the performance rating for air-cooled chillers relies on an entering dry-bulb air temperature of 95 °F. Performance is then evaluated at 25%, 50%, 75%, and 100%. These specified operating conditions provide a standard framework employed to evaluate the performance of various chiller technologies.

Fundamentally, the cooling loads of the shopping malls vary frequently during the day. Thus, the choice of appropriate chiller technology should consider its performance at both full and part-load conditions. In this study, the energy performance of several commercially available chiller technologies was evaluated using the IPLV rating method. The comparison includes scroll, screw, variable-speed screw (Screw VSD), centrifugal, and oil-free centrifugal chillers. For air-cooled systems, scroll chillers were further classified into capacities below 150 TR and above 150 TR. The corresponding performance comparison under different operating loads is presented in Figures 6 and 7.

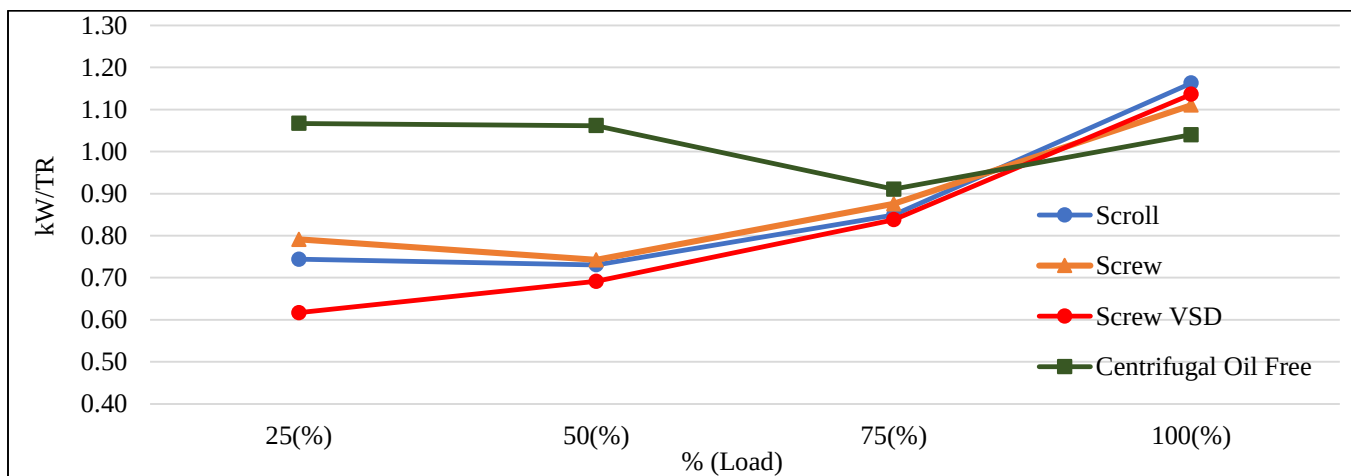


Fig. 6 Comparison of the energy performance of different air-cooled chiller technologies under various operating load conditions

Comparison of the energy performance of different air-cooled chiller techniques under varied operating load conditions is displayed in Figure 6. The results show that each chiller technology demonstrates different energy consumption characteristics, depending on the cooling load. It is obvious that the highest energy efficiency is obtained during part-load conditions, particularly between 50 and 75 percent of the rated

cooling capacity. On the other hand, energy efficiency decreases significantly when the operating load reaches full-load conditions. These findings clearly point out the significance of evaluating chiller performance under actual operating conditions where commercial air-conditioning systems normally operate at part-load rather than full-load.

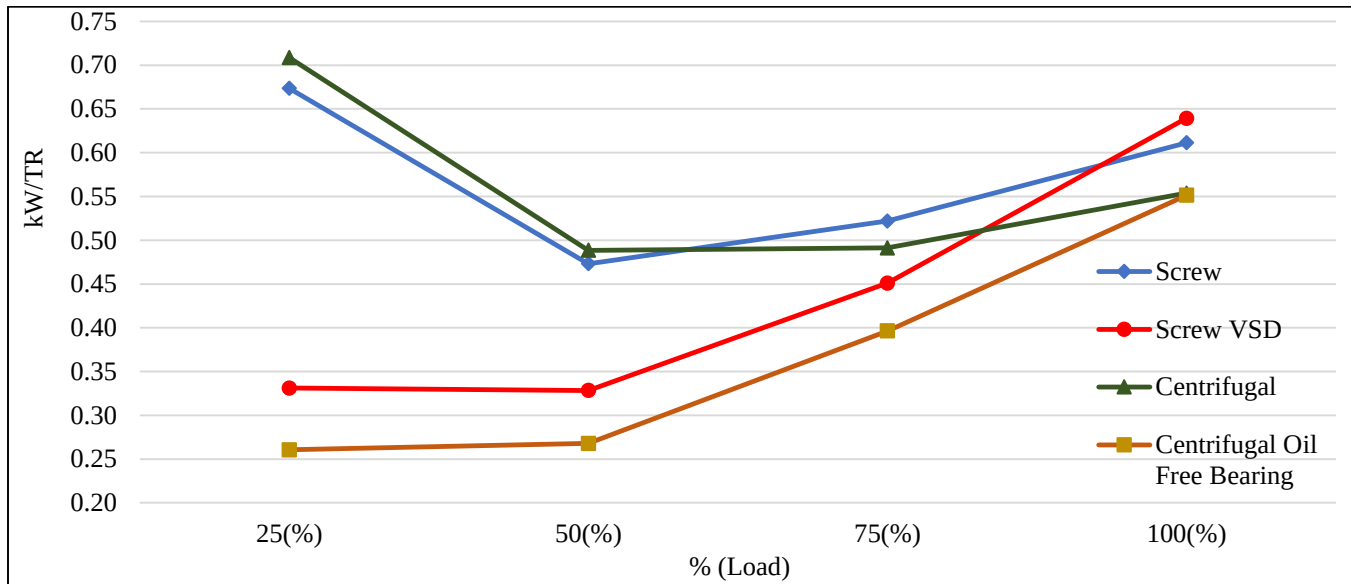


Fig. 7 Comparison of the energy performance of different water-cooled chiller technologies under different cooling load conditions

Figure 7 presents a comparison of the energy performance of different water-cooled chiller technologies subjected to different cooling loads. It is clear from this figure that different chiller technologies exhibit different energy performance under different cooling loads. The oil-free centrifugal chiller displays the minimum kW/TR values between 25% and 75% load, indicating better energy efficiency under part-load operation. As large commercial buildings usually function under part-load conditions for almost the day, this kind of chiller can provide better energy performance than other technologies. Conventional screw chillers show good performance at medium and high loads. However, the variable-speed screw chiller can regulate its compressor speed corresponding to the actual cooling demand, leading to improved energy efficiency over a wider operating range. Therefore, oil-free centrifugal chillers are suitable for applications where cooling demand is relatively constant, such as shopping malls, hospitals, data centers, and other large commercial buildings.

Based on the above discussion, it can be seen that many shopping malls in Thailand still experience difficulties in matching chiller operation with the actual cooling demand throughout the day. In many commercial buildings, Building Management Systems (BMS) are connected with Heating, Ventilation and Air Conditioning (HVAC) systems to monitor and control system operation in real time. However, the

operating conditions are still adjusted mainly by operators. As a result, the cooling capacity may not always correspond to the actual cooling load, leading to unnecessary electricity consumption [20, 21]. Recently, AI, IoT technologies and predictive analytics have been applied to HVAC systems, aiming to improve system operation and energy management. IoT devices can receive operating data continuously. At the same time, AI can process this data and modify them for selecting suitable operating conditions. Estimated cooling demand can be obtained from several parameters, including outdoor weather conditions, building occupancy, and historical operating data. With this information, the chiller system can automatically be adapted to the required cooling demand. Obviously, this method can improve system operation and simultaneously reduce improper energy consumption. Thus, the additional use of AI and IoT can be an effective alternative option for improving the energy efficiency of large air-conditioning systems in the future.

4.3. Energy Performance Evaluation and Payback Evaluation

To clearly evaluate the energy performance of examined chiller systems, the minimum energy performance requirement specified in ASHRAE Standard 90.1-2001 (ASHRAE, 2001–2005) was employed as a benchmark to compare with the measured energy performance of the chiller systems, expressed in kW/TR [17-19]. For water-cooled

centrifugal chillers with cooling capacities from 1,055 to 7,032 TR, the recommended energy performance is 0.560 kW/TR. This standard value was used as a reference to assess

the average energy performance of the three shopping malls. Table 5 summarizes the comparison of the measured kW/TR with the ASHRAE standard.

Table 5. Payback analysis of chiller replacement

Shopping Mall	Measured kW/TR)	Standard kW/TR	Difference in kW/TR	Cooling Capacity (TR)	Annual Cost Saving (THB)	Installation Cost (THB)	Payback Period (Years)
A	0.777	0.560	0.217	1,960	8,383,057	27,440,000	3.3
B	0.767	0.560	0.207	2,000	8,159,940	28,000,000	3.4
C	0.817	0.560	0.257	2,800	14,183,316	39,200,000	2.8

Table 5 presents the payback analysis based on the operation of the chiller systems for 12 hours per day and 365 days per year in the three shopping malls. The average electricity price in Thailand was assumed to be 4.5 THB/kWh. Among the three shopping malls, Shopping Mall C provides the shortest payback period of 2.8 years. This is because the average energy performance of the existing chiller system is 0.817 kW/TR, which is considerably higher than the ASHRAE standard value.

Therefore, the replacement of the present chiller with a high-efficiency chiller can provide better energy savings and reduce the payback period of investment. For comparison, Shopping Malls A and B show the calculated payback periods of 3.3 and 3.4 years, respectively. Technically, the average service life of a big centrifugal chiller with a capacity of 2,000 TR is around 20–25 years. Hence, the replacement of inefficient chillers with high-efficiency units can result in long-term economic savings.

4.4. Assessment of Greenhouse Gas Emissions from Electricity Consumption

The detailed comparison of electricity consumption and the corresponding greenhouse gas emissions is summarized in Table 6. The greenhouse gas emissions associated with electricity consumption were estimated using the carbon footprint methodology in accordance with ISO 14064-1:2006 [27].

In addition, the Greenhouse Gas (GHG) Protocol developed by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) were adopted as the reference framework for estimating organizational greenhouse gas emissions. It should be noted that this study considers only greenhouse gas emissions resulting from electricity consumption. Emissions associated with refrigerant leakage were not included in the present assessment.

Table 6. Electricity consumption and corresponding carbon dioxide equivalent emissions of air-conditioning cooling systems

Shopping Mall	Electricity Consumption per Floor Area (kWh/m ² year)	Annual Electricity Consumption (kWh/Year)	Carbon Dioxide Equivalent Emissions (TCO ₂ -eq/Year)
A	446.96	11,742,004.68	5,869.83
B	312.22	10,946,225.52	5,472.02
C	526.78	18,468,268.50	9,232.29

Table 6 presents an assessment of carbon dioxide equivalent (CO₂-eq) emissions related to the electricity consumption of air-conditioning cooling systems in the three shopping malls.

The results suggest that Shopping Mall B exhibits the lowest CO₂-eq emissions among the three cases. This is fundamentally due to its efficient operational management strategy, particularly the appropriate scheduling of chiller operation based on cooling load demand.

This innovative approach clearly reduces electricity consumption and simultaneously decreases carbon dioxide equivalent emissions. Furthermore, the addition of renewable energy sources, particularly solar Photovoltaic (PV) systems for daytime operation, is an effective technique for obtaining

carbon neutrality in air-conditioning cooling systems. The use of solar-generated electricity during peak daylight hours, especially between 09:30 and 15:00, can greatly offset grid electricity consumption.

Technically, it can be estimated that a 1 MW solar PV system can generate approximately 1,500,000 kWh annually, as per a study on solar power generation in Thailand [16]. Solar PV integration can further reduce the need for grid electricity and lower carbon dioxide equivalent emissions.

Table 7 presents a comprehensive analysis of electricity production from solar photovoltaic systems for air-conditioning cooling systems at different installed capacities. The proposed solar PV installation was evaluated based on each shopping mall's total electricity consumption.

Table 7. Electricity generation from solar photovoltaic systems of different capacities for air-conditioning cooling systems toward carbon neutrality

Shopping Mall	Annual Electricity Consumption (kWh/Year)	Installed Solar PV Capacity (MW)	Electricity Generated by Solar PV (kWh/Year)	Remaining Grid Electricity Consumption (kWh/Year)	Carbon Dioxide Equivalent Emissions (TCO ₂ -eq/Year)
A	11,742,004.68	4.50	6,750,000.00	4,992,004.68	2,495.50
B	10,946,225.52	4.00	6,000,000.00	4,946,225.52	2,472.62
C	18,468,268.50	6.50	9,750,000.00	8,718,268.50	4,358.26

According to the results shown in Tables 6 and 7, air-conditioning cooling systems contribute to more than 60% of total electricity consumption in all three shopping malls, indicating that cooling systems are the main source of energy use. Among the three case studies, Shopping Mall C exhibits the highest electricity consumption and carbon dioxide equivalent emissions, with an average value of 9,232.29 tCO₂-eq/year. To reduce grid electricity consumption through solar Photovoltaic (PV) integration, an installed PV capacity of at least 6.50 MW, consistent with the value reported in Table 7, is required, depending on the available installation area. In this case, the amount of carbon dioxide equivalent pollution produced from air conditioning can be lowered by about 52.8%. Shopping Mall A has an annual electricity consumption of 11,742,004.68 kWh and average carbon dioxide equivalent emissions of 5,869.83 tCO₂-eq/year. The addition of a solar PV system with a minimum capacity of 4.50 MW could decrease carbon dioxide equivalent emissions from air-conditioning cooling by nearly 57.50%. Similarly, Shopping Mall B employs 10,946,225.52 kWh/year and generates an average of 5,472.02 tCO₂-eq/year. The installation of a solar PV system with a minimum capacity of 4.00 MW can evidently reduce carbon dioxide equivalent emissions from air-conditioning cooling by about 54.81%.

Clearly, these results indicate that the three shopping malls install solar PV systems at the recommended capacities, carbon neutrality for air-conditioning cooling systems can be obtained. Moreover, an innovative integrated approach that combines renewable energy with advanced operational management to match cooling production to actual cooling load can further decrease electricity consumption and carbon dioxide equivalent emissions.

5. Conclusion

The energy consumption and CO₂-eq emissions from air-conditioning cooling systems were systematically monitored and analysed in three shopping malls in Thailand: Shopping Malls A, B, and C. The electricity consumption per unit cooling area was calculated as 446.96, 312.22, and 526.78 kWh/m²·year, respectively. These values vary significantly due to differences in the functional characteristics and service arrangements of each shopping mall. In particular, Shopping Mall C includes both working spaces and shopping areas. This makes the cooling load management more difficult to perform during certain periods. So, cooling supply cannot be

effectively adjusted to match actual cooling demand, leading to an annual electricity consumption of 18,468,268.50 kWh and carbon dioxide equivalent emissions of 9,232.29 tCO₂-eq/year. In contrast, Shopping Mall B exhibits the lowest electricity consumption per unit cooling area. The mall consumes 10,946,225.52 kWh/year and produces 5,472.02 tCO₂-eq/year, meaning that the cooling system management is efficient. Especially, the chiller system operates three chillers per day starting at 09:30, with scheduled shutdowns at 17:00, 20:00, and 21:00. In addition, chilled water pumps are installed with variable speed drives operating at 42 Hz, whereas the operation of cooling tower fans is set at 45 Hz. These measures provide better control of cooling production in response to real cooling demand. Therefore, Shopping Mall B exhibits greater potential for obtaining carbon neutrality in its air-conditioning cooling systems as compared to the other two shopping malls. Based on the findings of this study, an innovative and practical approach is the addition of solar Photovoltaic (PV) systems for daytime electricity supply.

The use of a minimum solar PV capacity of approximately 4 MW clearly enhances the reduction of carbon dioxide equivalent emissions related to air-conditioning cooling by up to 54.81%. Therefore, this novel approach shows significant potential for promoting the transition toward carbon neutrality in major commercial buildings. However, a limitation of this investigation is that sensitivity and uncertainty analyses were not conducted to examine the effects of the alternations of significant operating and economic parameters, such as electricity tariffs, operating hours, cooling load, and system performance. In addition, a comprehensive Life-Cycle Assessment (LCA) was not included in the parameters of the present study. Therefore, sensitivity and uncertainty analyses as well as life-cycle assessment should be included in future research to examine the usefulness of the proposed evaluation approach under various operating conditions and to provide an in-depth assessment of its environmental impacts.

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