Engineering and Applied Science Research 2023;50(4):372-381 Research Article

EASR

Engineering and Applied Science Research

https://www.tci-thaijo.org/index.php/easr/index

Published by the Faculty of Engineering, Khon Kaen University, Thailand

Analysis of potential energy and cost savings of replacing air-cooled chillers with water-cooled chillers: A case study in hotel building in tropical climate

Arka Dwinanda Soewono*[1)], Ivan Agustinus Kusmanto[1)], Marten Darmawan[1)] and Sheila Tobing[2)]

[1)]Department of Mechanical Engineering, Faculty of Engineering, Atma Jaya Catholic University of Indonesia, Jakarta 12930, Indonesia
[2)]Department of Energy System Engineering, Faculty of Engineering, University of Indonesia, Jakarta 10430, Indonesia

Received 30 April 2023
Revised 10 July 2023
Accepted 12 July 2023

Abstract

Selecting the type of chillers to be used in commercial buildings is critical considering their high energy consumption, which consequently requires the use of chillers with higher efficiency in order to improve the energy efficiency of buildings and reduce their carbon footprint. Through a case study in a commercial resort, this research presents an energy consumption analysis of the replacement of air-cooled chillers with water-cooled chillers. The energy savings were calculated based on not only the simulation software but also the actual energy consumption data after the installation of the water-cooled chillers. The energy analysis indicated that the use of water-cooled chillers to substitute the air-cooled chillers in the resort resulted in energy saving of around 17.5% with a reduction of 2860 tonnes of CO_2 equivalent emission per year. Meanwhile, the cost analysis showed that the life-cycle cost of the water-cooled chillers is around 13.4% less. These findings demonstrate the potential of using water-cooled chillers as a replacement for air-cooled chillers in existing commercial buildings to reduce energy consumption and its associated carbon emission without compromising the buildings' indoor comfort. This option can be an appeal to building owners as it has some evident economic benefits.

Keywords: Chiller, Cooling load, Energy saving, Life-cycle cost, Carbon emission

Nomenclature

e	Cost escalation rate
d	Discount rate
N	Cost analysis period
TR	Tons of Refrigeration
TRh	Ton-Hours of Refrigeration

Abbreviations

AHRI	Air Conditioning, Heating and Refrigeration Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEMS	Building Energy Management System
CLTD	Cooling Load Temperature Difference
COP	Coefficient of Performance
CPA	Chiller Plant Automation
IPLV	Integrated part load value
PVF	Present value factor
TREND	TICA chiller automation software

1. Introduction

Many large commercial buildings, such as hotels and offices, utilize chiller-based air conditioning systems to provide cooling energy and maintain thermal comfort for the building occupants. However, such chiller systems typically consume a considerable portion of the building's electrical energy, with previous studies noting how the air conditioning system can contribute to over half of the total electricity usage in commercial buildings [1-3], with the chiller system accounting for about 40-50% of the total air conditioning energy use [4, 5]. Furthermore, inadequate maintenance often causes an excessive increase in chiller power consumption [6].

As part of carbon and energy reduction strategies, several countries have introduced national standards and guidelines for chiller energy efficiency and mandated minimum energy performance for chiller systems installed in medium and large buildings [7], yet the current standards used to assess and improve the energy performance of chillers still possess a limitation. The guidelines often are not effective in representing the chiller under actual operating conditions, mainly since the energy consumed by the chiller is not a linear function of the operating temperatures [8] and is highly affected by the cooling demand [9].

Other strategies have also been proposed to improve energy performance and lower building electricity demand. The most common research works involve the optimization of the chiller system design using building energy simulation software to forecast power consumption and minimize carbon emissions [10-12]. , while others utilize a data-driven algorithm and machine learning to enhance the efficiency of chiller plants [13-16]. Implementing a data-driven approach combined with energy management software improved

*Corresponding author.
Email address: arka.soewono@atmajaya.ac.id
doi: 10.14456/easr.2023.40

the efficiency of the multiple-chiller plant in a commercial hospital by around 12% [17]. Even though many studies have shown the applicability of simulation and prediction models for optimizing chiller operations, they are rarely adopted by engineers outside the academic world due to the perceived impracticality and uncertainties associated with the optimization method [18].

Another method proposed to improve the efficiency of chiller-based air conditioning systems is by adding variable speed drives to control the flow of chilled water or condenser as well as the cooling tower fans [19-21], or installing variable-frequency compressors [22, 23]. It is evident that many chiller plants are often saddled with overdesign problems, where designers tend to choose oversized equipment with excess capacity to meet the safety factors and to ensure the client's indoor comfort requirements, resulting in the building chiller systems usually being operated at less than 50% capacity [24, 25]. The presence of the variable speed drives can therefore ensure the near-optimum operation of the chiller and its components, with reports showing that using variable speed drives in chiller systems can yield an annual energy saving of around 25%–28% [26, 27]. One main drawback of this approach is that the successful application of chiller systems with variable flow depends on how the flow and chiller capacity can be adjusted in response to the changing load conditions, rendering the potential energy saving of the chiller system subject to the limitation of pumps and other equipment. Moreover, chiller operators or technicians may not have the information regarding the relation between the cooling energy output and the electricity demand of each component, which is needed to maximize the energy saving from the chiller system. Lastly, it is worth noting that modifying existing chiller systems in buildings by adding variable speed drives is relatively uncommon in developing countries, mainly due to a lack of technical expertise, the warranty concern and the cost consideration.

A simpler and more practical solution to improve building energy efficiency is to install a more efficient chiller. This approach is beneficial since the majority of buildings are not new. Thus, the opportunity of reducing worldwide energy consumption and carbon emissions from the building sector relies heavily on upgrading existing buildings [28, 29]. Several studies have demonstrated the energy-saving potential of high-efficiency chillers in commercial buildings such as hotels and shopping centers [30-34], reporting energy savings of between 10 and 38 percent from replacing outdated chillers [33-35].

In general, many medium and large buildings utilize either air-cooled or water-cooled vapor compression chillers in their air-conditioning system. A recent report indicates that air-cooled chillers occupy the largest market segment [36], which is mainly attributed to economic reason: the investment and operational costs to install and maintain air-cooled chillers are lower than the costs of using water-cooled chillers [37, 38]. In contrast, water-cooled chillers usually have a longer lifespan and higher full-load efficiency [17, 39], which will likely reduce the building electricity consumption and emission if installed in a large commercial building. The main challenge, though, is to justify the economic benefit of purchasing replacement chiller for the building owners.

The current study aims to examine the energy-saving opportunity that can be achieved by replacing air-cooled chillers with water-cooled chillers in an existing hotel building in Bogor, Indonesia. The novelty of this case study is that the specific energy consumptions of the air-cooled and water-cooled chillers were compared based on not only the predicted simulation results from building energy management software but also the actual electricity usage by the resort following the chiller replacement. In addition, the cost analysis for both chiller systems is performed to demonstrate the economic feasibility of renovating the chiller plant in a commercial building. Given the apparent benefit from a business perspective, building owners can eventually be encouraged to invest in more energy-efficient chillers to make commercial buildings such as hotels more sustainable.

2. Research methods

2.1 Description of the chiller systems

The chiller plants being studied are operated in a luxury resort and convention center in Bogor, West Java, Indonesia (6°39'S, 106°53'E). The outdoor weather in the resort is a tropical wet climate, with average temperatures year-round ranging between 28°C and 31°C and humidity of 71 to 85%. The chiller plant was designed according to local standard SNI 03-6390-2011 with outdoor temperature assumed to have an average maximum dry bulb temperature of 33°C and an average maximum wet bulb temperature of 27°C. In addition, the chiller was also designed to maintain indoor temperature at 23°C ± 1°C with relative humidity of 45% ± 5% per the local standard SNI 03-6572-2001. The resort has five floors with a total air-conditioned area of 7,738 m^2. The ground floor is for the hotel lobby, ballrooms, meeting rooms and restaurants, while the 1^{st} to 4^{th} floors are for the guest rooms.

Before the replacement, air-cooled chillers with screw compressors had been used to supply the resort's cooling energy from 1999 to 2019. Each air-cooled chiller had a nominal capacity of 155 TR (Tons of Refrigeration) or 545.11 kW and a coefficient of performance (COP) of 5.71 at full load. In 2020, these air-cooled chillers were replaced by water-cooled chillers with screw compressors, with each water-cooled chiller having a nominal capacity of 185 TR (650.62 kW) and a coefficient of performance (COP) of 6.07 at full capacity. The specifications of the air-cooled and water-cooled chillers are summarized in Table 1.

Table 1 Specifications of air-cooled and water-cooled chillers

Specification	Air-Cooled Chiller	Water-Cooled Chiller
Capacity	155 TR	185 TR
Compressor Type	Screw - Fixed Speed	Screw - Fixed Speed
Manufacturer	McQuay	TICA
No. of Unit	3	2
Chiller Design Efficiency	0.632 kW/TR	0.579 kW/TR
Refrigerant	HCFC-22	HCFC-134a
Installation Year	1999	2020

Based on the manufacturer’s datasheet, the integrated part load values (IPLV) of the McQuay air-cooled chillers and TICA water-cooled chillers were 3.82 and 5.59, respectively. Both types of chillers met the minimum COP and IPLV requirements of the Air Conditioning, Heating and Refrigeration Institute (AHRI) standard 550/590. The performance curves for both McQuay and TICA chillers are shown in Figure 1. The characteristic curve for the air-cooled McQuay chillers was obtained from the field measurement, while the chiller performance of water-cooled chillers was based on the TICA technical sheet.

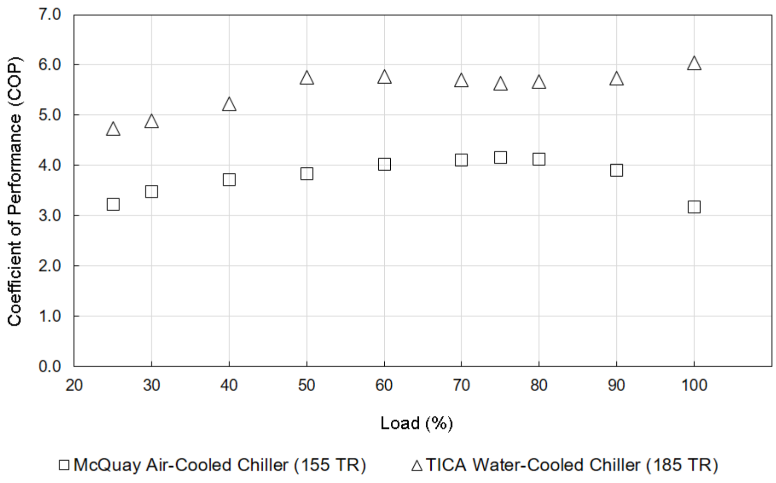
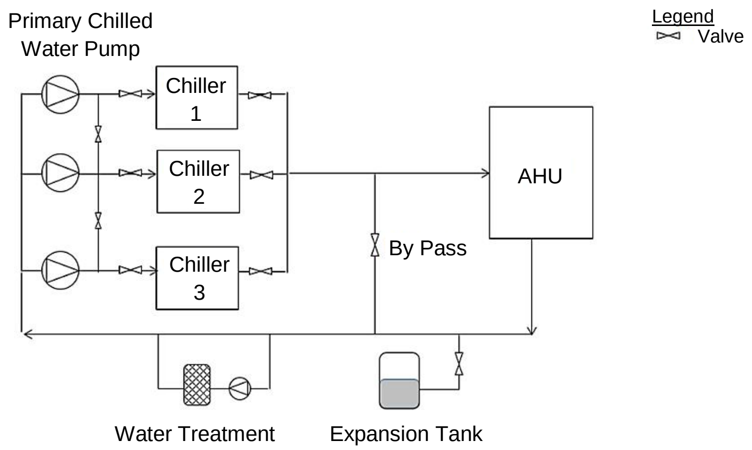
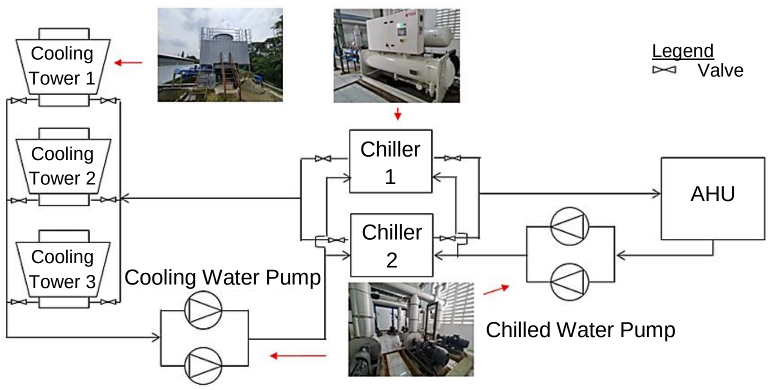


Figure 1 Performance curve of air-cooled and water-cooled chillers

The designs for the air-cooled and water-cooled chiller plants are shown in Figure 2. The chiller plants were designed with all chillers running in 24/7 operating mode. The cooling capacity distribution between chillers was asymmetrical, and the hydraulic circuit was arranged in a parallel configuration for ease of maintenance. The previous chiller plants were equipped with three air-cooled chillers that used refrigerant R-22 with a total cooling capacity of 465 TR. Following the manufacturer's guideline, the supply chilled water temperature was controlled at 7°C. Starting in 2020, the chiller plants used two water-cooled chillers using refrigerant R134a with a total cooling capacity of 370 TR. The identical setting was the chilled water temperature, which was set at 7°C. The temperature of the water entering the condensers was maintained at 30°C using cooling towers.



(a)



(b)

Figure 2 Schematics of chiller plants: (a) previous air-cooled chillers; (b) current water-cooled chillers

The specifications of the main auxiliary cooling equipment for both the air-cooled and water-cooled chiller systems are shown in Table 2. Since air-cooled chillers work by absorbing heat from processed water, they need less auxiliary equipment and consequently have lower acquisition costs. In contrast, water-cooled chillers require additional cooling towers and condenser pumps, increasing their total ownership costs.

Table 2 Auxiliary equipment of air-cooled and water-cooled chiller systems

Equipment	Air-Cooled Chiller	Water-Cooled Chiller
Cooling Tower	Not Applicable	Variable Flow Cooling Tower
Type	-	Cross-flow
Capacity	-	2336 kW
Number of unit	-	2
Input Power	-	5,5 kW
Chiller Water Pump	Variable Flow Pump	Variable Flow Pump
Flow	48,66 m³/hour	48,66 m³/hour
Input power	22.5 kW	22 kW
Head	25 m	25 m
Number of unit	3	2
Condenser Water Pump	Not Applicable	Variable Flow Pump
Flow	-	60,82 m³/hour
Input power	-	11 kW
Head	-	15 m
Number of unit	-	2

2.2 Energy analysis

A walkthrough energy audit was conducted on the chiller systems in 2019 (before the COVID-19 pandemic) and 2022 (after the pandemic). The energy audit process involved collecting primary data, such as the total energy consumption of the building and monthly electrical usage of the chiller systems, and compiling secondary data, which included information on equipment specifications, daily operating patterns of the air conditioning systems, and maintenance records. The energy audit was carried out in compliance with the ISO 50002:2014 guideline. The primary purpose of the audit was to record and analyze the daily and monthly power consumption of the equipment of the chiller systems based on the data collected from the energy management software and monthly electricity bills. In order to identify the potential energy reduction of the chiller systems, the specific energy consumption of the chillers was calculated using Equation (1):

$$Specific\ Energy\ Consumption = \frac{Chiller\ Electricity\ Consumption\ (kWh)}{Total\ Building\ Cooling\ Load\ (TRh)} \tag{1}$$

The chillers' power consumption and building cooling load data were obtained from the TREND Chiller Plant Automation (CPA) and Building Energy Management System (BEMS) software, respectively.

The specific energy consumption of the chillers was calculated for the period from January to June, which was chosen due to the availability of data on the actual electricity consumption of the water-cooled chillers in 2022. Moreover, this data can also reflect the region's dry and wet seasons. Similar to a previous study [33], the potential energy saving of a water-cooled chiller was analyzed based on two different scenarios:

- The January-June 2019 cooling load data was used as an input for TICA Chiller Selection software to forecast the power consumption of the water-cooled chillers. The predicted power consumption of the water-cooled chillers was then compared to the actual air-cooled chiller power consumption to calculate the estimated energy saving;
- Using an assumption that the average specific energy consumption of the chiller remains constant, the cooling load data from January-June 2022 was used to predict the power consumption of the air-cooled chillers. The predicted power consumption of the air-cooled chillers was then compared to the actual water-cooled chiller power consumption to obtain the actual energy savings;

The electricity consumption of the chillers was also used to estimate their annual CO_2 equivalent emissions using Equation (2):

$$Annual\ CO_2\ (eqv.) = Electricity\ Consumption\ (kWh) \times Emission\ Factor\ (tCO_2/kWh) \tag{2}$$

Based on a recent study, the electricity in Bogor is supplied by steam-electric coal power stations, which yield an emission factor of 2,030 tCO_2/kWh [40].

2.3 Life-cycle cost analysis

The modified life-cycle cost analysis for both air-cooled and water-cooled chiller plants was also performed. The analysis period was taken as 20 years, which represents the recommended manufacturer's lifetime for both chillers. Based on the interview with the chiller suppliers, the lifetime of auxiliary equipment is often equal to that of the chillers during the design phase, thus requiring no replacement equipment during the analysis period. Other assumptions made during the life-cycle cost analysis include the following:

- The analysis only focus on investment cost, operational and maintenance cost. It does not include disposal costs;
- The average of investment and maintenance cost of the equipment from two different chiller suppliers were used in the analysis;
- All monetary values presented in the analysis are in nominal 2022 dollars;
- The analysis was performed with the assumption of a constant exchange rate of (Indonesian Rupiah) IDR 15,500/USD;

- Since the hotel has an electricity requirement above 200 kVA, which is categorized as a large business group (B-3) by Indonesia National Electricity Company (PLN), the electricity tariff for electricity is USD 0.075/kWh;
- According to Indonesia Water Supplies Company, the water tariff for a hotel is set at USD 0.08/m3;
- Based on the average inflation rate in Indonesia from 2019 to 2021, the escalation rate for the electricity and water tariff, as well as maintenance cost was set at 2% per annum;
- The discount rate for the cost analysis was fixed at 7.5%;
- With the intention of simplify the calculation, the operational and maintenance costs occur at the end of the year;

In order to adjust for the depreciation of money due to inflation, the net present values of the life-cycle costs of each chiller plant were calculated using Equation (3) and (4):

$$Life\text{-}cycle\ Cost = Annual\ Cost\ (USD) \times PVF \quad (3)$$

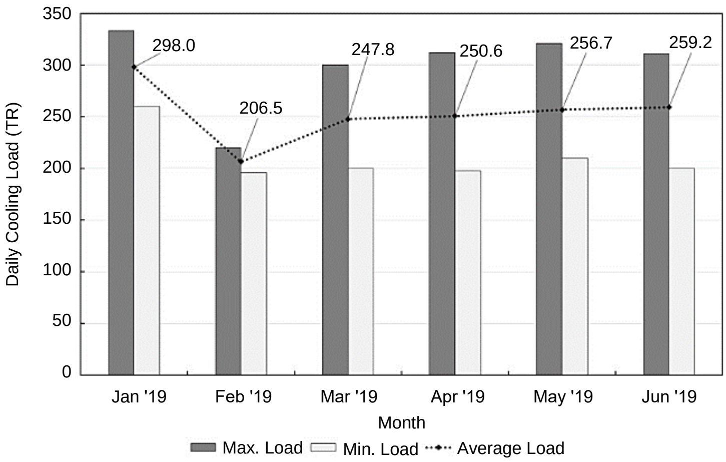
$$PVF = \frac{1-(1+e)^N(1+d)^{-N}}{(d-e)} \quad (4)$$

PVF is the unit Present Value Factor, N is the analysis period (lifespan of the chiller), e is the escalation rate, and d is the discount rate used in the cost analysis. The present value of the life-cycle cost was calculated for both the operational (electricity and water) and maintenance costs. Afterward, the total life-cycle cost of the chiller plants can be derived from the addition of the present value of operational and maintenance costs to the initial investment cost.

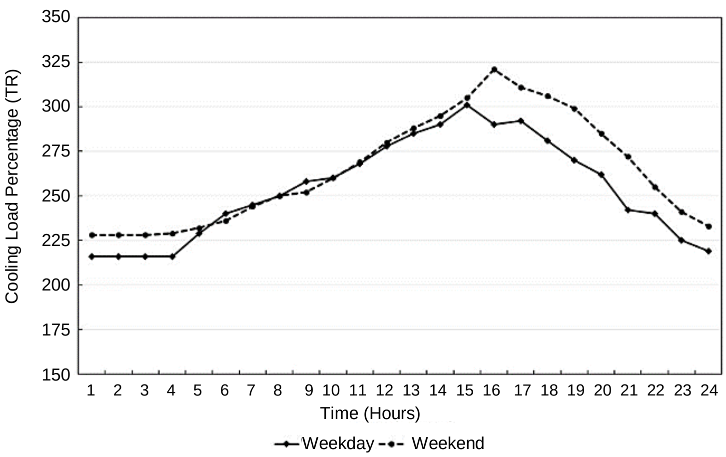
3. Results and discussion

3.1 Chiller energy and emission analysis

Based on the data collected from the walk-through energy audit, the building cooling load was calculated based on the Cooling Load Temperature Difference (CLTD) method using TREND software. It was found that the average cooling load per unit area of the resort and convention center is 0,115 kW/m^2, which is within the range of the standard cooling load of 0.11 kW/m^2 to 0.17 kW/m^2) for a hotel in the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) handbook. Figure 3 shows the resort's cooling load profile for January to June 2019, with the hourly cooling load profile shown for January 2019.



(a)



(b)

Figure 3 Daily maximum and minimum (a), and hourly (b) cooling load profile of the resort

The audit, using the historical data and monthly electricity bills, revealed that the air-cooled chiller plants accounted for more than 50% of the total energy used in 2019. Due to the high energy usage of the air-cooled chillers, a significant potential of energy saving in the resort can therefore be achieved by employing more efficient water-cooled chillers. Table 3 compares the energy consumption of air-cooled chiller plant compared to the predicted energy usage of water-cooled chiller plant for the month of January 2019 to June 2019. The actual power consumption of the air-cooled chillers for each month was obtained from the CPA software. TICA Chiller Selection software was used to estimate the electricity consumption of the water-cooled chillers. The monthly specific energy consumptions were calculated using Equation (1). Based on the manufacturers' datasheet, the air-cooled and water-cooled chillers were operated at a capacity of 50% to 70% load to satisfy the cooling energy demand. At these load conditions, both chillers were likely operating under optimal part-load Coefficient of Performance (COP).

Table 3 Energy consumptions of air-cooled and water cooled chillers for January to June 2019

Daily Cooling Load		**Air-Cooled Chillers Energy Consumption Details**			**Water-Cooled Chillers Energy Consumption Details**			**Energy Saving**
Month	**Average (TR)**	**Cooling Energy (TRh)**	**Power (kWh)**	**Specific Energy Cons. (kW/TR)**	**Cooling Energy (TRh)**	**Power (kWh)**	**Specific Energy Cons. (kW/TR)**	**Savings (kWh)**
Jan'19	297.8	153,056.8	113,109	0.74	153,056.8	99,460	0.65	13,649
Feb'19	206.5	96,140.3	75,374	0.78	96,140.3	67,427	0.70	7,947
Mar'19	247.8	132,201.8	102,192	0.77	132,201.8	86,023	0.65	16,169
Apr'19	250.6	138,750.0	106,560	0.77	138,750.0	87,807	0.63	18,753
May'19	256.7	146,307.6	109,877	0.75	146,307.6	91,847	0.63	18,030
Jun'19	259.2	138,403.1	106,432	0.77	138,403.1	88,667	0.64	17,765
Average	253.1	134,143.3	102,257.3	0.76	134,143.3	86,871.9	0.65	15,385.5

According to the Air Conditioning, Heating and Refrigeration Institute (AHRI) benchmark [33], installing the new water-cooled chiller could improve the rating of the chiller plants from "Good" to "Excellent" since the specific energy consumption of the chiller plants decreased from 0.76 to 0.65, which indicated an increase in the efficiency of chillers. From the data in Table 3, the water-cooled chillers in the resort generated an estimated electricity consumption reduction of 17,885 kWh per month, representing an energy saving of 15.05% from January to June 2019.

In order to examine the actual energy savings of the water-cooled chillers, a similar energy analysis on the chiller plants was performed from January 2022 to June 2022. Table 4 shows the actual energy consumption of the water-cooled chillers obtained from the CPA software. Based on the cooling energies required during that period and chiller performance data from the manufacturer, the electricity consumption of air-cooled chillers could be estimated. From January 2022 to June 2022, the utilization of the water-cooled chillers yielded a decrease in energy consumption by 17.52%, resulting in an average energy savings of 19,588 kWh per month. In this case study, the energy saving achieved by replacing air-cooled chillers with water-cooled chillers is in agreement with the previous findings [41, 42].

Table 4 Energy consumptions of air-cooled and water cooled chillers for January to June 2022

Daily Cooling Load		**Air-Cooled Chillers Energy Consumption Details**			**Water-Cooled Chillers Energy Consumption Details**			**Energy Saving**
Month	**Average (TR)**	**Cooling Energy (TRh)**	**Power (kWh)**	**Specific Energy Cons. (kW/TR)**	**Cooling Energy (TRh)**	**Power (kWh)**	**Specific Energy Cons. (kW/TR)**	**Savings (kWh)**
Jan'22	290.9	166,617.5	124248	0.75	166,617.5	101938	0.61	22,310
Feb'22	200.3	101,869.5	80770	0.79	101,869.5	67613	0.66	13,157
Mar'22	238.2	148,109.1	112778	0.76	148,109.1	91922	0.62	20,856
Apr'22	276.7	156,262.3	117727	0.75	156,262.3	96593	0.62	21,134
May'22	288.1	160,254.1	117368	0.73	160,254.1	98419	0.61	18,949
Jun'22	274.0	156,096.8	117677	0.75	156,096.8	96553	0.62	21,124
Average	261.4	148,201.6	111,761.3	0.76	148,201.6	92,173.0	0.62	19,588.3

The data regarding the chillers' energy saving and emission analysis over the January-June 2022 period are shown in Table 5. From the power consumption average from January 2022 to June 2022, the monthly carbon dioxide (CO_2) equivalent emission for each chiller was calculated using Equation (2). The predicted life-cycle carbon emissions were calculated based on the expected lifespan of 20 years of the air-cooled and water-cooled chillers. It was estimated that about 117.5 MWh of electricity could be saved by replacing the timeworn air-cooled chillers with newer water-cooled chillers in a six-month period. Moreover, about 17.5% or 2860 tonnes of annual carbon emissions associated with the chillers' electricity usage can be reduced. Similar decreases in CO_2 emissions attributed to the installation of more efficient chillers in commercial buildings have been reported in earlier studies [5, 41]. These findings suggest that water-cooled chillers should be chosen for medium and large building applications due to their inherent higher efficiency and that air-cooled chillers should be installed in commercial buildings only if there is insufficient installation space and water supply.

Table 5 Summary of energy analysis for January to June 2022

	Unit	Air-Cooled Chillers	Water-Cooled Chillers	Difference
A. Energy Consumptions				
Total Cooling Energy Generation	TRh	889,209.4	889,209.4	
Total Power Consumption	kWh	670,567.5	553,038	117,529.5
Monthly Specific Energy Consumption	kW/TR	0.76	0.62	0.13
Actual Differences in Chillers' Power Consumption from 2019 to 2022	kWh			60,506
B. Green House Gas Emissions				
CO_2 (eqv.) Emissions per Month	Tonnes	1361.3	1122.7	238.6
Annual CO2 (eqv.) Emissions	Tonnes	16335.0	13472.0	2863.0
Life-cycle CO2 (eqv.) Emissions	Tonnes	326700.5	269440.1	57260.4

In general, carbon reduction strategies in the building sector typically focus on reducing life-cycle emissions from building materials, optimizing design of buildings, and improving the energy use of buildings [43]—with the first two mainly applicable for new buildings. Considering that new buildings only represent a small percentage of the buildings around the world [28], managing and reducing energy use in existing buildings can be the better strategy to meet lower carbon emission targets. Improvement in thermal performance of building envelope can help to lessen cooling load of a building and leads to reduction in carbon emission by 5-10% [44]. The operational energy demand in buildings can also be reduced by replacing outdated building appliances, especially those with high-electricity consumption such as chillers. As shown in this case study, replacing outdated chillers can lead to a decrease of 2870 tonnes (17,5%) of carbon emissions in the resort in one-year period, which is significant since the reported average yearly emissions of other comparable hotel operations in developing countries are only around 7000 tonnes of carbon [45]. A significant reduction in the carbon emissions, which was attributed to the chiller replacement, was achieved primarily because the energy consumption for the operation of air conditioning equipment (i.e., chillers) contributed the largest proportion to the resort's carbon emissions as the electricity was supplied by coal. The findings concerning the energy and carbon emissions in this study demonstrate how replacing outdated building equipment may provide an opportunity for building owners to meet the targets of carbon emission reduction in the building sector.

3.2 Life-cycle cost analysis of chiller plant

The life-cycle cost comparison between the air-cooled and water-cooled chiller plants took into account investment costs associated with the initial purchasing cost of equipment, operational cost (electricity and water costs), and maintenance cost, as listed in Table 6 for each type of chiller. To calculate the investment cost, the actual acquisition cost was provided by the supplier, and this purchase cost was further adjusted following the inflation rate issued by the Bank of Indonesia to obtain the current nominal value of the air-cooled chillers.

Regarding the operational cost, the electricity costs were based on the electricity consumption data from Table 3 and 4, while the water usage cost was associated with the consumption of water required to replenish the water lost to evaporation in the water-cooled chiller plants, which was predicted in the energy audit to reach 69.6 m^3 per year. Lastly, the maintenance costs covered the fee required to conduct regular inspections of filter driers and pipes, check oil levels and leaks, and perform preventive measures to reduce vibration, with additional cost of chemical-based water treatment for the water-cooled chillers.

Table 6 Summary of investment and annual costs for air-cooled and water-cooled chiller plants

	Air-Cooled Chiller Plant	Water-Cooled Chiller Plant
Investment Cost (USD)		
Chiller	96809.03	79130.32
Chiller Pump	8870.97	8387.10
Cooling Tower	0.00	17225.81
Condenser Pump	0.00	5419.35
AHU	54161.29	54161.29
Operational Cost (USD)		
Electricity Usage	97426.78	81505.84
Water Usage	0.00	56.13
Maintenance Cost (USD)		
Regular Treatment	1935.48	1935.48
Water Treatment	0.00	309.68

Table 7 summarizes the life-cycle cost of the air-cooled and water-cooled chiller plants. The present values of the annual electricity and water costs as well as the maintenance costs were calculated using Equations (3) and (4). When compared to air-cooled chillers, the water-cooled chillers had lower operating cost of the water-cooled due to the decrease in electric consumption, which evidently offset their higher investment cost. Consequently, the estimated overall life-cycle cost of the water-cooled chiller plants was USD 179404.17 less than that of the previously used air-cooled chiller plants, indicating a cost saving of around 13.44%. The lower life-cycle cost of the water-cooled chillers presented in this case study is consistent with the findings of the previous studies [39, 41].

Table 7 Life-cycle cost analysis for air-cooled and water-cooled chiller plants

	Air-Cooled Chiller	Water-Cooled Chiller	Difference
Investment Cost (USD)	159841.29	164323.87	-4482.58
Electricity and Water Cost (USD)	97426.78	81505.84	15864.82
Maintenance Cost (USD)	1935.48	2245.16	-309.68
No. of Years	20	20	
Discount Rate per Year	0.075	0.075	
Cost Escalation Rate per Year	0.02	0.02	
Life-cycle Electricity and Water Cost (USD)	1151741.24	964193.61	187547.63
Life-cycle Maintenance Cost (USD)	22880.53181	26541.4169	-3660.88509
Overall Life-cycle Cost of Chiller Plant (USD)	1334463.06	1155058.90	179404.17

From a business perspective, the installation of water-cooled chillers in medium and large buildings is recommended due to their lower life-cycle costs than those of air-cooled chillers. However, it is often challenging to persuade building owners or operators to replace outdated air-conditioning equipment, especially chillers, with newer and more energy-efficient types given the costly initial investment and the difficulty to show the direct benefit of the reduction in the building carbon emissions following the chiller replacement. Therefore, it is imperative that the life-cycle cost analysis be performed to illustrate how the cost savings attributed to the lower energy demand of more energy-efficient chillers can offset the initial high costs. This financial benefit means that the replacement of old chillers with new chillers may be an appealing option for the building owners or operators, as evident in the present study.

In term of industry trend, water-cooled chillers used to represent the largest share of the chiller market, but the trend has been reversed recently, with air-cooled chillers becoming relatively more popular for commercial and office buildings in developing countries due to size and cost considerations [36]. On top of the higher initial costs, it is often assumed that the operational costs for running water-cooled chillers are higher owing to the additional energy consumed by the condenser pumps and cooling tower fans in such chillers. The findings, nonetheless, have confirmed how the higher efficiency of water-cooled chillers could compensate for the extra electricity usage from the pumping and cooling tower systems. Not only that, in a tropical climate, the water-cooled chillers will likely have better energy performance since they are more resistant to ambient temperature and humidity fluctuations in tropical environments. To verify this claim, further studies can examine how the chillers work in different building types, diverse operating conditions, or different climate zones.

This study also illustrated the importance of regularly updating and introducing stricter standards for energy performance ratings for chillers. While most manufacturers currently follow the Coefficient of Performance rating requirements of the AHRI standard 550/590, this standard requires different minimum COP levels for different chiller types for labeling or certification purposes. The minimum required COP of air-cooled chillers ranges from 2.40 to 3.06, while the COP of water-cooled chillers ranges from 3.80 to 6.39 at full load [7]. Hence, it is easier for most air-cooled chillers to meet the minimum full load COP requirement as they tend to have lower COP than their water-cooled counterparts.

4. Conclusions

In this study, energy and life-cycle cost analyses were performed for chiller plants in a commercial resort, which was aimed to compare the energy consumption of air-cooled and water-cooled chillers and examine their potential energy and cost savings. The findings of this study are as follow:

- It was found that the actual energy usage of the water-cooled chillers was 17.52% less, yielding an average monthly energy savings of 19,588 kWh from January 2022 to June 2022. These energy savings amounted to a reduction of 2860 tonnes of carbon emissions on an annual basis.
- Even though the capital costs of purchasing water-cooled chiller equipment were more expensive than the air-cooled chiller, the life-cost analysis showed that the overall cost of running a water-cooled chiller plant for the resort was 13.44% lower.

The findings confirm that water-cooled chillers are more suitable for commercial buildings, such as hotels, due to their higher efficiency and lower life-cycle costs. It should be noted that the scope of the energy and life-cycle cost savings presented in this study may not be applicable to other hotels and commercial buildings since the energy saving potential for buildings can be influenced by many factors such as climate, building design and age, and operating hours. Future studies should then consider different types of buildings, particularly those with higher energy loads such as hospitals or those under different climate zones, to assess the energy saving benefit of upgrading outdated air conditioning equipment. Furthermore, the study should be expanded to compare the energy use and cost of operating a new high efficiency air-cooled chiller plant versus a water-cooled chiller plant. This study can be valuable to building owners and operators to inform them the economic value of replacing older equipment with more energy-efficient type, which will make their buildings more sustainable. When more similar studies have been conducted, the benchmarks of energy saving and the corresponding emission reduction from the chiller replacement scenarios can be established, which will be beneficial to legislators in developing strategies to enhance the sustainability of commercial buildings.

5. Acknowledgements

The authors would like to thank the resort management for their assistance during the energy audit.

6. References

[1] Lin M, Afshari A, Azar E. A data-driven analysis of building energy use with emphasis on operation and maintenance: a case study from the UAE. J Clean Prod. 2018;192:169-78.

[2] Xiong W, Wang J. A semi-physical static model for optimizing power consumption of HVAC systems. Control Eng Pract. 2020;96:104312.

[3] Sala-Cardoso E, Delgado-Prieto M, Kampouropoulos K, Romeral L. Predictive chiller operation: a data-driven loading and scheduling approach. Energy Build. 2020;208:109639.

[4] Yu J, Liu Q, Zhao A, Qian X, Zhang R. Optimal chiller loading in HVAC system using a novel algorithm based on the distributed framework. J Build Eng. 2020;28:101044.

[5] Saidur R, Hasanuzzaman M, Mahlia TMI, Rahim NA, Mohammed HA. Chillers energy consumption, energy savings and emission analysis in an institutional buildings. Energy. 2011;36(8):5233-8.

[6] Lin CM, Wu CY, Tseng KY, Ku CC, Lin SF. Applying two-stage differential evolution for energy saving in optimal chiller loading. Energies. 2019;12(4):622.

[7] Yu FW, Chan KT, Sit RKY, Yang J. Review of standards for energy performance of chiller systems serving commercial buildings. Energy Procedia. 2014;61:2778-82.

[8] Zhang D, Luh PB, Fan J, Gupta S. Chiller plant operation optimization with minimum up/down time constraints. IEEE Robot Autom Lett. 2018;3(1):9-15.

[9] Liu PL, Chuang BS, Lee WS, Yeh PL. An analytical solution of the optimal chillers operation problems based on ASHRAE guideline 14. J Build Eng. 2022;46:103800.

[10] Al-Waked R, Nasif MS, Groenhout N, Partridge L. Energy performance and CO_2 emissions of HVAC systems in commercial buildings. Buildings. 2017;7(4):84.

[11] Yu FW, Chan KT, Sit RKY. Carbon emissions of chiller systems in Hong Kong hotels under climate change. Strateg Plan Energy Environ. 2014;34(2):39-64.

[12] Yu FW, Chan KT, Sit RKY. Environmental benefits of sustainable chiller system under climate change. Int J Sustain Build Technol Urban Dev. 2014;5(2):109-14.

[13] Chaerun Nisa E, Kuan YD. Comparative assessment to predict and forecast water-cooled chiller power consumption using machine learning and deep learning algorithms. Sustainability. 2021;13(2):744.

[14] Wang H, Lei Z, Zhang X, Zhou B, Peng J. A review of deep learning for renewable energy forecasting. Energy Convers Manag. 2019;198:111799.

[15] Ho WT, Yu FW. Chiller system optimization using k nearest neighbour regression. J Clean Prod. 2021;303:127050.

[16] Zheng Z, Li J, Duan P. Optimal chiller loading by improved artificial fish swarm algorithm for energy saving. Math Comput Simul. 2019;155:227-43.

[17] Alonso S, Morán A, Prada MÁ, Reguera P, Fuertes JJ, Domínguez M. A data-driven approach for enhancing the efficiency in chiller plants: a hospital case study. Energies. 2019;12(5):827.

[18] Yan C, Cheng Q, Cai H. Life-cycle optimization of a chiller plant with quantified analysis of uncertainty and reliability in commercial buildings. Appl Sci. 2019;9(8):1548.

[19] Yu FW, Chan KT. Optimization of water-cooled chiller system with load-based speed control. Appl Energy. 2008;85(10):931-50.

[20] Jiang X, Long W, Li M. Optimum control strategy for all-variable speed chiller plant. J Cent South Univ. 2011;18:573-9.

[21] Furlong J, Crowther H. Optimizing chillers and towers. ASHRAE J. 2004;46(7):34-45.

[22] Hsu CN, Wang SH. Evaluating the performance of water chillers equipped with constant- or variable-frequency centrifugal compressors. Processes. 2021;9(6):1039.

[23] Trautman N, Razban A, Chen J. Overall chilled water system energy consumption modeling and optimization. Appl Energy. 2021;299:117166.

[24] Yu FW, Chan KT, Sit RKY, Yang J. Critique of the design and operation of sustainable air-cooled chillers in commercial buildings. Energy Eng. 2015;112(3):55-79.

[25] Kim SH, Kim DG. Survey study on optimal cooling equipment capacity in office buildings. J Archit Inst Korea. 2007;23(8):247-54.

[26] Ma K, Zhao T, Shen D, Liu M. Web based chiller plant optimal control-a case study. Procedia Eng. 2017;205:967-74.

[27] Ha J, Cho S, Kim H, Song Y. Annual energy consumption cut-off with cooling system design parameter changes in large office buildings. Energies. 2020;13(8):2034.

[28] Dahlhausen M, Heidarinejad M, Srebric J. Building energy retrofits under capital constraints and greenhouse gas pricing scenarios. Energy Build. 2015;107:407-16. https://doi.org/https://doi.org/10.1016/j.enbuild.2015.08.046.

[29] Partridge LE, Loughnane EJ. Committed carbon—upgrading existing buildings. Struct Des Tall Spec Build. 2008;17(5):989-1002.

[30] Kaya D, Alidrisi H. Energy savings potential in air conditioners and chiller systems. Turkish J Electr Eng Comput Sci. 2016;24(3):935-45.

[31] Yatim A, Prima JA, Jofansya MA, Alhamid MI, Budihardjo, Lubis A. Performance of oil-free water-cooled chiller for a shopping center air conditioning system. IOP Conf Ser Earth Environ Sci. 2021;673:12010.

[32] Lyu W, Wang Z, Li X, Xin X, Chen S, Yang Y, et al. Energy efficiency and economic analysis of utilizing magnetic bearing chillers for the cooling of data centers. J Build Eng. 2022;48:103920.

[33] Anandh N, Kumar P. A case analysis on energy savings and efficiency improvement of a chiller plant in a luxury hotel building. Int Energy J. 2021;21(4):447-56.

[34] Marjianto A, Hafthirman, Darmanto PS. Energy and cost saving potential of hotel air conditioning using magnetic bearing chiller in Jakarta. Int J Innov Mech Eng Adv Mater. 2021;3(1):1-11.

[35] Yu FW, Chan KT, Sit RKY, Yang J. Performance evaluation of oil-free chillers for building energy performance improvement. Procedia Eng. 2015;121:975-83.

[36] Naguib R. The changing landscape of chillers' energy efficiency. Energy Eng. 2011;108(4):25-45.

[37] Naguib R. Total cost of ownership: for air-cooled and water-cooled chiller systems. ASHRAE J. 2009;5(4):42-8.

[38] Howell RH, Land DW, Scheideman ED. Air-cooled HVAC retrofit: safe bet for Vegas schools. ASHRAE J. 2004;46(5):28-32.

[39] Hvac A, Khalil E. Energy evaluations between air-cooled vs water-cooled cooling systems in egyptian private buildings. 3rd International Energy Conversion Engineering Conference; 2005 Aug 15-18; San Fransisco, USA. San Fransisco: American Institute of Aeronautics and Astronautics; 2005.

[40] Azmi R, Maslahat P, Wahono JW. The carbon footprint from the power plant in Indonesia and renewable energy supply for reduce the carbon emission. IOP Conf Ser Earth Environ Sci. 2022;997:12008.

[41] Yik FWH, Lai JHK, Fong NK, Leung PHM, Yuen PL. A case study on the application of air- and water-cooled oil-free chillers to hospitals in Hong Kong. Build Serv Eng Res Technol. 2011;33(3):263-79.
[42] Tam LS, Lau KC, Shek LC. Achievements and participation of the pilot scheme for fresh water evaporative cooling towers. Proc. of Symposium on Solution, Breakthrough & Technical Approach for Wider User of Water-cooled Air Conditioning System; 2006 Dec 8; Hong Kong. Hong Kong: Association of Energy Engineers; 2006. p. 1-9.
[43] Gao Z, Liu H, Xu X, Xiahou X, Cui P, Mao P. Research progress on carbon emissions of public buildings: a visual analysis and review. Buildings. 2023;13(3):677.
[44] Dakwale VA, Ralegaonkar RV. Review of carbon emission through buildings: threats, causes and solution. Int J Low-Carbon Technol. 2012;7(2):143-8.
[45] Abeydeera LH, Karunasena G. Carbon emissions of hotels: the case of the Sri Lankan hotel industry. Buildings. 2019;9(11):227.