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Site Investigation on Water Cooled Chiller Plant for Energy Conservation and Environmental Impact Reduction of a Large Shopping Mall

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Abstract. The investigated shopping mall building comprises indoor shopping, entertainment, and food centers which are simultaneously open from 10 a.m. to 10 p.m. The building is conditioned from a central plant incorporated water cooled chiller system comprises three identical chillers of 1245 tons of refrigeration (TR) cooling capacity per chiller. This paper is aimed to evaluate energy and environmental performances of water cooled chiller plant and develop energy conservation and environmental impact reduction strategies to the building. Chillers' operational data were hourly recorded which include power consumption, condensing and evaporating temperatures, evaporator-condenser approach temperature, ambient temperature and flowrate of chilled and cooling water. Annual data of chiller operation were recorded. Chillers' energy performance, indirect environmental impact and main factors that influenced the chiller plant performance were hourly and daily evaluated. The results showed that the chiller could steadily operate all year round with load factor range 70%-100% and annual average load factor of 85.8%. Annual energy consumption of the chiller plant was 7,158 MWh accounted for 26.1% of total energy use and environmental impact due to energy consumption was 6,039 tons CO_{2e}. Annual Coefficient of Performance (COP) and overall efficiency of the chiller were 5.64 and 0.62 $kW.TR^{-1}$ respectively. Energy Intensity Use (EIU) of the building was 459.89 $kWh.m^{-2}.y^{-1}$.The results also showed that energy consumption and environmental impact of the chillers were sensitive to load factor.

INTRODUCTION

Energy consumption of both residential and commercial has steadily increased, globally reaching values between 20% and 40% in developed countries [1]. In Indonesia, energy consumption of the commercial buildings sector alone was accounted for 5.3% of the country energy use. The sector includes office buildings, hospitals, hotels, shopping malls and airports. The energy consumption growth of the commercial sector was the second highest just after industry with consumption growth of 5.68% per year [2]. Energy saving potential of the sector was estimated to be ranging from 10% up to 30% and energy saving target in 2025 was estimated to be 15% [3-5]. It has been specifically reported that shopping malls, one of the commercial building types including retail stores, are energy intensive buildings with specific energy consumption ranging from 500 to 1000 $kWh.m^{-2}.y^{-1}$. This energy intensity corresponds to three times that of conventional residential buildings and five times that of office buildings [6]. Other study also reported that food retail stores, as a conventional practice, had energy intensity ranging from 346 to 700 $kWh.m^{-2}.y^{-1}$ and for non-food retail stores from 146 to 293 $kWh.m^{-2}.y^{-1}$ [7].

Moreover, some retail stores include massive use food refrigeration systems which are particularly carbon intensive in terms of direct emissions. Emissions of hydrofluorocarbon (HFC) refrigerants from refrigeration and air conditioning systems can further contribute to environmental impact because the global warming potential (GWP) of the refrigerant gases. Studies identified energy-efficiency strategies in food and non-food retail buildings have been reported in [6,8-10]. In shopping mall buildings, the growth in the energy use by air conditioning systems is remarkably significant. Energy consumption for air conditioning system could reach or even more than 50% of

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building consumption [1,11], moreover studies on shopping malls showed that air conditioning was the single largest electricity consuming service accounting for 47-54% of the total electricity consumption followed by electric lighting with energy consumption of 33-38% [12]. Air conditioning and electric lighting are very important for shopping malls because modern shopping arcades tend to have much larger lighting load, higher businesses density and, consequently, larger air conditioning demand. The increase of electrical energy consumption is one of the major issues that is raised by global use of air conditioning system, which could be a drawback mainly due to its growth in developing countries [13].

Most of the energy use in shopping mall buildings is for the provision of lighting, air conditioning and refrigeration. Especially for tropical countries, air conditioning equipment is specified corresponding to the sensible heat capacity to reduce temperature and substantial latent heat capacity to remove moisture from the conditioned room air. As the number of shopping mall buildings is growing rapidly, a study on air conditioning system energy performance and factors influenced for evaluation of energy saving potential in the buildings appears to be interesting for the researchers. In addition, very few studies about the topics are reported in literatures. The works carried out in this paper were focused on site evaluation of energy and environmental performances of water cooled chiller plant (a type of central air conditioning system applied in shopping malls). The evaluation included the chiller operation, load factor, energy consumption, environmental impact especially due to energy use, Coefficient of Performance and power efficiency, factors influenced the performance, as well as potential strategies for optimizing energy efficiency and CO_2 emissions reduction of the buildings.

METHODS

Hourly operational data of the chiller plant starting from 10 a.m. to 10 p.m. for one-year were gathered which include chillers' operational parameters such as: power consumption, load factor, condensing and evaporating temperatures, evaporator-condenser approach temperatures, ambient temperature and flowrate of chilled and cooling water. The data also involve refrigerant pressure of the refrigeration system and pressures of chilled and cooling water. Data were retrieved from chillers' monitoring systems and some additional instrumentations such as water flow meters, power meters (for chillers, chilled and cooling water systems, air handling units (AHUs) and fan cooling unit (FCUs) and cooling tower system). and ambient temperature measurement. Data obtained were recorded manually every hour into computer data sheets for a period of one year. Recorded data were, then, processed and then analyzed for comprehensive chiller performance evaluation and investigated factors that influenced their performance.

Energy performance of the chiller plant which is commonly known as *COP* (Coefficient of Performance) is determined from the chiller plant cooling capacity (Q_{cool}) and compressors power consumption (W_{comp}) as expressed in Eq.(a) (where the units of Q_{cool} and W_{comp} are in kW).

$$COP = \frac{Q_{cool}}{W_{comp}} \qquad \text{a)}$$

Other performance parameters which are also commonly used include *COPS* (Coefficient of Performance System) and overall efficiency (*OE*) in terms of the full-load kW per ton of refrigeration ($kW.TR^{-1}$). The COPS is determined by including pump power (W_{pump}) and fan power (W_{fan}) for AHUs, FCUs and cooling towers (Eq. (b) and (c)).

$$COPS = \frac{Q_{cool}}{W_{comp} + W_{pump} + W_{fan}} \qquad \text{b)}$$

$$OE = \frac{W_{comp}(in\,kW)}{Q_{cool}(in\,TR)} \qquad \text{c)}$$

Indirect environmental impact of the chiller plant due to energy consumption was also estimated referred to BS EN 378-1 Standard [14] and greenhouse gases (GHG) emissions factor (β) for electricity generation in Indonesia was based on regional grade emissions factor of Jamali (Jawa-Madura-Bali) published by Government of Indonesia in 2014 for about 0.84 $tCO_{2e}.MWh^{-1}$ [15]. Direct impact due to refrigerant leakage and recovery is not included.

Description of the Shopping Mall and Chiller Plant

A fully air conditioned shopping malls built during the 2010s was selected for the study. It is a modern shopping centers located in West Java of 60,000 m^2 gross floor area. The mall was equipped with centralized air conditioning (AC) or chiller plant. The chiller plant comprises cooling tower system, central air handling units (AHUs) and localized fan coil units (FCUs). The main plant incorporated three water cooled chillers at rated 1245 TR (tons of refrigeration) each. Therefore, total capacity of installed chillers is 3735 TR. Each chiller has a rated coefficient of performance (COP) of 6.24 with overall efficiency of 0.56 kW.TR^{-1}. The chillers use centrifugal compressors and R-134A as their refrigerant. Two of the three chillers are simultaneously operated to satisfy the mall cooling demand.

For building energy management purposes, separate energy meters were installed to record electricity use for the entire buildings with five main group of services included: the chiller plant; the pumping and fan systems (chilled and cooling water, cooling tower, AHUs and FCUs systems); the circulation and communal areas for lighting, escalators, lifts, fire hydrant and water supply systems; the lighting and small powers of mall-1 and mall-2. Electricity of mall-1 and mall-2 was for lighting in the shops and retail outlets. Lighting density loads and the corresponding electricity consumption of the shopping mall varied, depending generally on functional and artistic requirements as well as the trading hours.

RESULTS AND DISCUSSION

Hourly Performances

Fig. 1(a) shows hourly variation of the chiller plant retrieved from one-month data. From the figure, it can be seen that peak ambient temperature of the day in the investigated month obtained from 1 p.m. to 3 p.m. This figure also shows the condensing and evaporator temperatures which are relatively constant and it is not directly affected by ambient temperature. It is because the heat rejection through cooling tower is mainly affected by wet bulb temperature of the ambient air, not dry-bulb temperature (ambient temperature). Moreover, regular cleaning on the cooling tower fill and water spray system by maintenance team can make the heat rejection perform well.

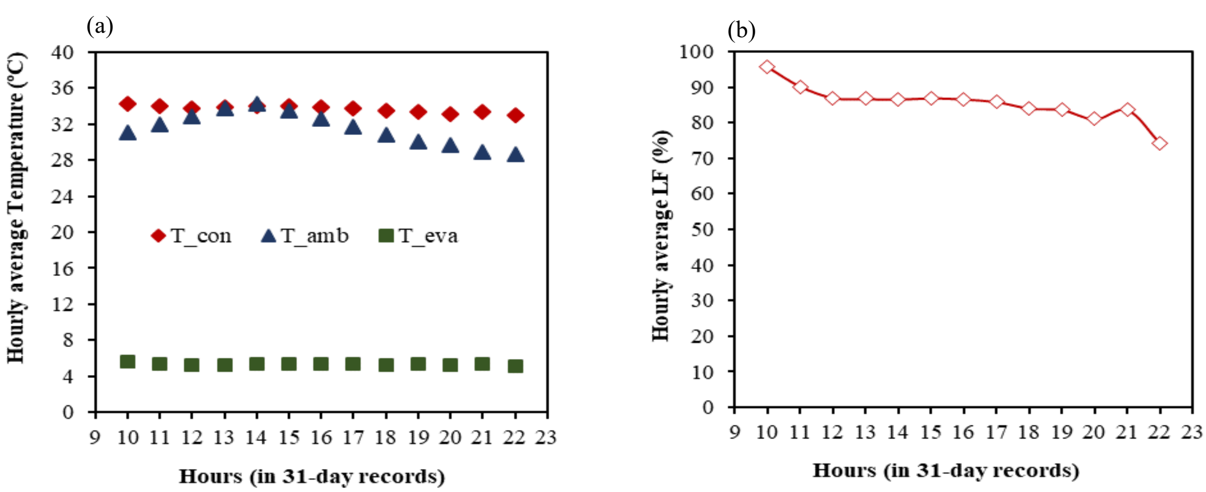

FIGURE 1. Real time variation of: (a) condensation, evaporation and ambient temperatures; (b) Load Factor (LF) presented hourly from one-month operation data

Fig. 1(b) shows load factor of the chiller plant. At the beginning of daily operation, the load factor is high reaching 97% due to high load of the warm air in the entire building. The load factor gradually decreases in two hours then remains constant until 5 p.m. The load factor of the chiller plant is substantially fluctuated during the last two-hours operation before the mall is closed. This is because of one chiller has been stopped. The change of chiller operation has made the recorded data become unstable.

Hourly variation of the chiller performance (COP) which is calculated based on cooling capacity and compressor power consumption is shown in Fig. 2 (a). While Fig. 2 (b) shows the COPS of the plant. COPS is determined similar to COP but COPS involves not only compressor power but also power consumption of chilled and cooling water pumping system, AHU and FCU as well as power consumption of the cooling tower. From the figures, it can be indicated that chiller plant performance followed the trend of plant load factor.

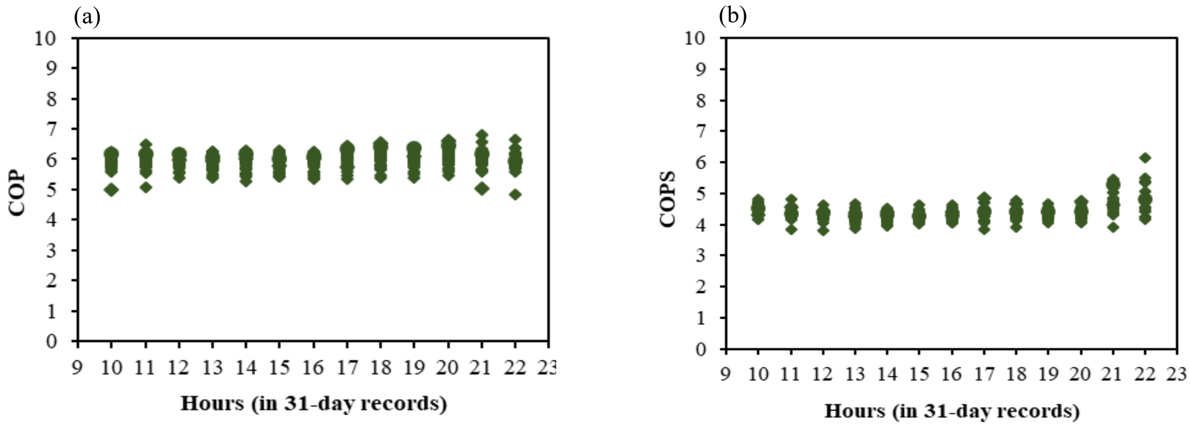

FIGURE 2. Real time variation of (a) COP and (b) COPS presented hourly from one-month operation data

Fig. 3. shows overall efficiency in $kW.TR^{-1}$ and CO_2 emissions of the chiller plant. The overall efficiency of the chiller plant is following the trend of its COP. While CO_2 emissions is a little bit high at the beginning; relatively constant from 10 a.m. to 8 p.m.; and steeply low at the last two hours because of energy consumption and mall cooling demand decreases. This is as the results of some shops and retails closed, consequently one chiller and its auxiliary equipment are also gradually shut down.

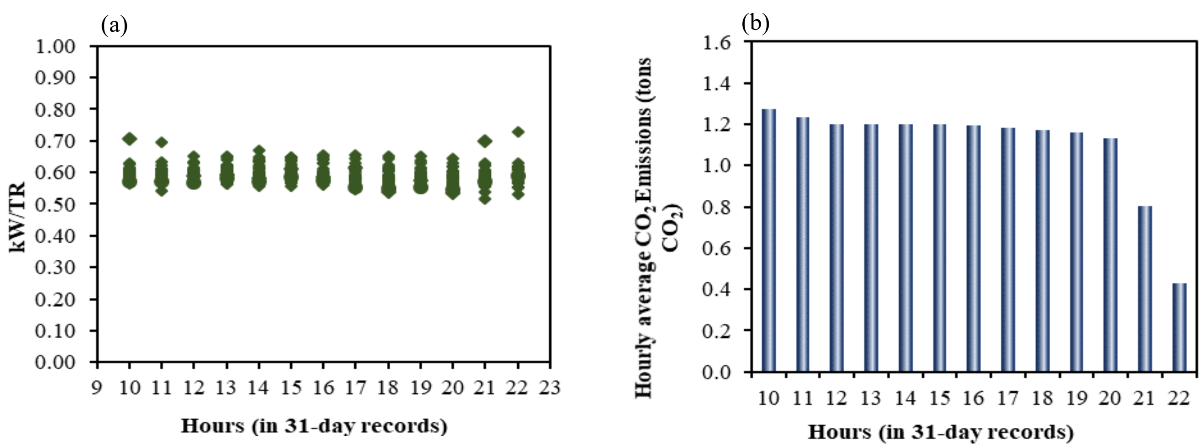

FIGURE 3. Real time variation of: (a) kW/TR and (b) CO_2 emissions presented hourly from one-month operation data

Daily Performances

In order to obtain wider view on the chiller plant performance, daily chiller energy and environmental performances are also presented. Figs. 4-6 show daily variation of energy and environmental performances of the chiller plant presented daily for a year operation period. Fig. 4 presents instant cooling demand and power consumption (including power consumption for pumps and fans) of the whole air conditioning system. Chiller plant instant power consumption varies from 1476 kW to 1855 kW for year round with average of about 1652 kW. It is relatively persistent compared with instant cooling capacity of the chiller ranging from 5853 kW to 7630 kW. Annual average instant cooling capacity is 6790 kW. These results in annual average energy performances of the chiller plant expressed as COP and COPS are 5.64 and 4.11 respectively. While overall efficiency is 0.62 $kW.TR^{-1}$ (Fig. 5). This indicated that the chiller plant performs less efficient compared with the specified efficiency of 0.56 $kW.TR^{-1}$ which also means the chiller plant consumes more energy every ton of cooling supplied to the building.

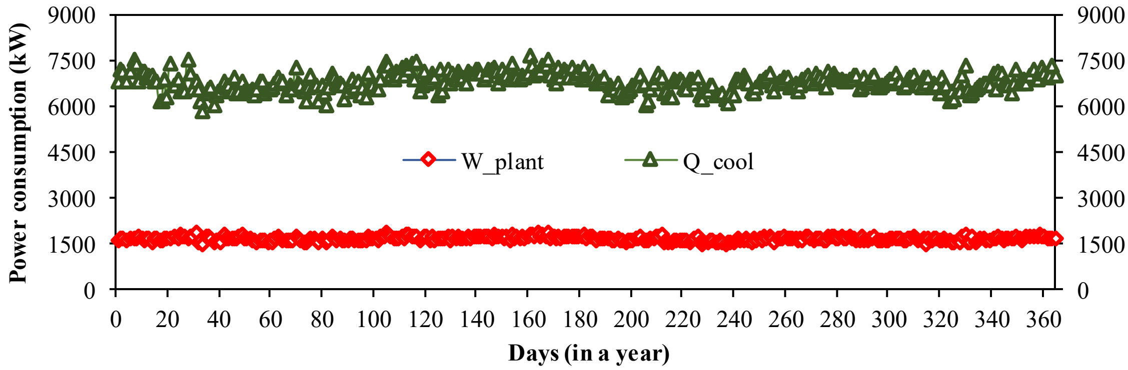

FIGURE 4. Instant cooling capacity and power consumption including power consumption for pumps and fans presented daily from one-year operation data

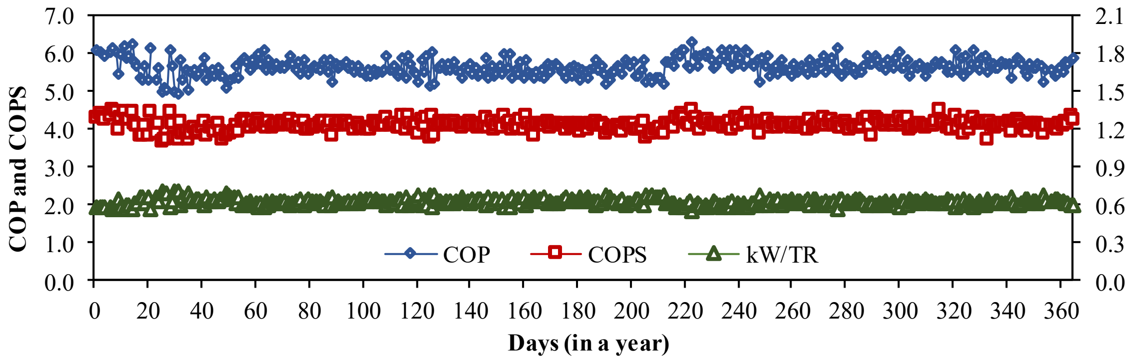

FIGURE 5. Real time variation of the COP, COPS and Overall Efficiency presented daily from one-year operation data

Daily indirect environmental impact of the chiller plant due to energy consumption is presented in Fig. 6. The impact is determined based on greenhouse gases (GHG) emissions factor for electricity generation in Indonesia. Direct emissions from refrigerant leakage and recovery are not included in this study. It is found that annual indirect impact of the chiller plant is 6,039 tons CO_{2e} with daily average reaching 16.66 tons CO_{2e}.

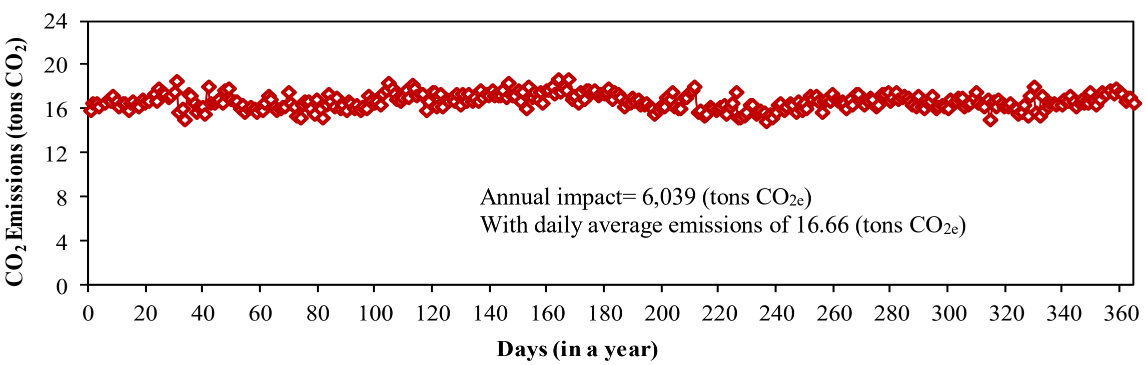

FIGURE 6. Real time variation of the CO_2 emissions presented daily from one-year operation data

Analyses of Factors Affect the Chiller Performance

Figs. 7-10 show factors that may affect the energy and environmental performances of the chiller plant. Daily average data for one year are used. Fig. 7 presents daily variation of three operation parameters include ambient, condensation and evaporation temperatures. Theoretically, condensation and evaporation temperatures of refrigerant can affect refrigeration performance. Higher condensation temperature and lower evaporation temperature make the compressor lift, pressure ratio and power increase. Consequently, the energy performance decreases [16]. Daily variation of condensation and evaporation temperatures are nearly constant throughout the year. There is small fluctuation occurs on condensation temperature as shown in Fig. 7. This is in agreement with hourly results described previously.

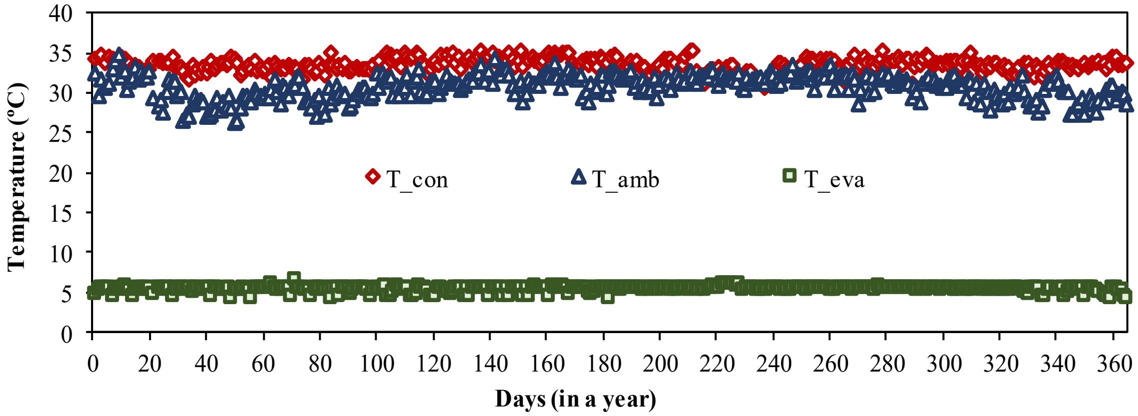

FIGURE 7. Real time variation of the condensation, evaporation and ambient temperatures presented daily for one year

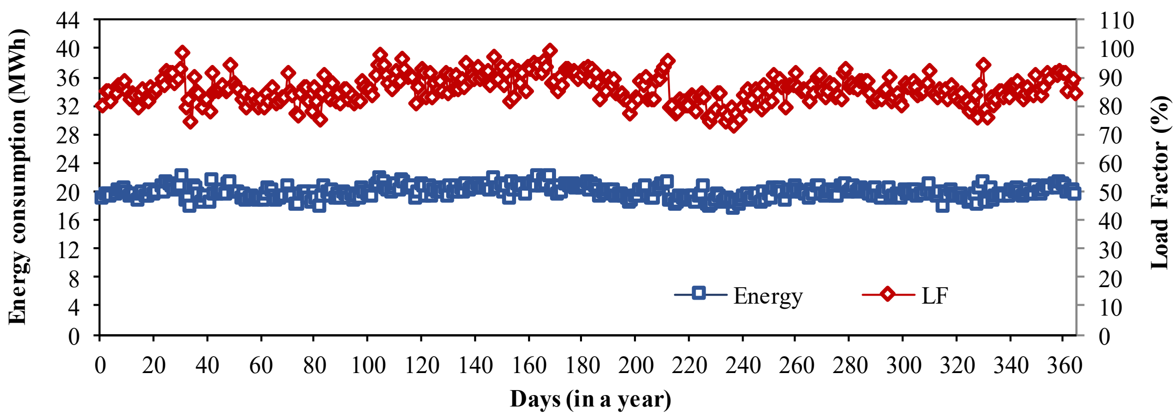

FIGURE 8. Real time variation of the energy consumption and Load Factor (LF) presented daily for one year

Energy consumption and environmental impact of the chiller plant are found to be significantly influenced by load factor (Figs. 6 and 8). This is also corresponding the hourly data as presented in Figs. 1(b) and 3(b). From the figures, it can be seen that both parameters fluctuate following the load factor of the chiller. Regression analysis results also show that load factor has strong correlation to power consumption and environmental impact with determination coefficient (R^2) of 0.9136 as shown in Figs. 9(a) and 10(b). The correlation signifies that the correlated parameters move in the same direction. Power consumption and environmental impact increases for about 29% when the chiller plant operates with load factor increases from 70% to 100%. The correlation of the load factor to power consumption and environmental impact is also shown in Figs. 9(a) and 10(b).

Fig. 9(b) shows the strength of relationship between load factor to cooling capacity of the chiller plant. The correlation signifies that load factor also positively influence the cooling capacity but it is not as strong as the power consumption. When the chiller plant operates with load factor increases from 70% to 100%, the cooling capacity improves for about 22%. Meanwhile, Fig. 10(a) presents relationship between load factor and the COP. It is found that the load factor negatively affects the COP of the chiller plant. The COP decreases when the load factor increases. This is as the results of the cooling capacity improvement of the chiller plant obtained from the increase of load factor is far lower than the increase of power consumption. From the analyses of this study, it was found that chiller plant could perform closed to the specification when operated at load factor ranging from 70% to 85%.

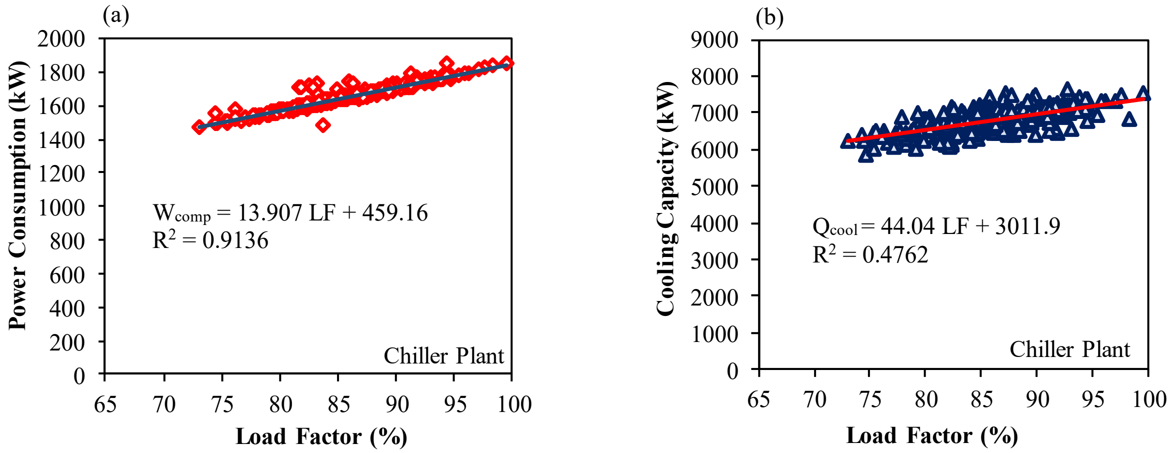

FIGURE 9. Regression analysis the effects of load factor (LF) on: (a) power consumption and (b) cooling capacity

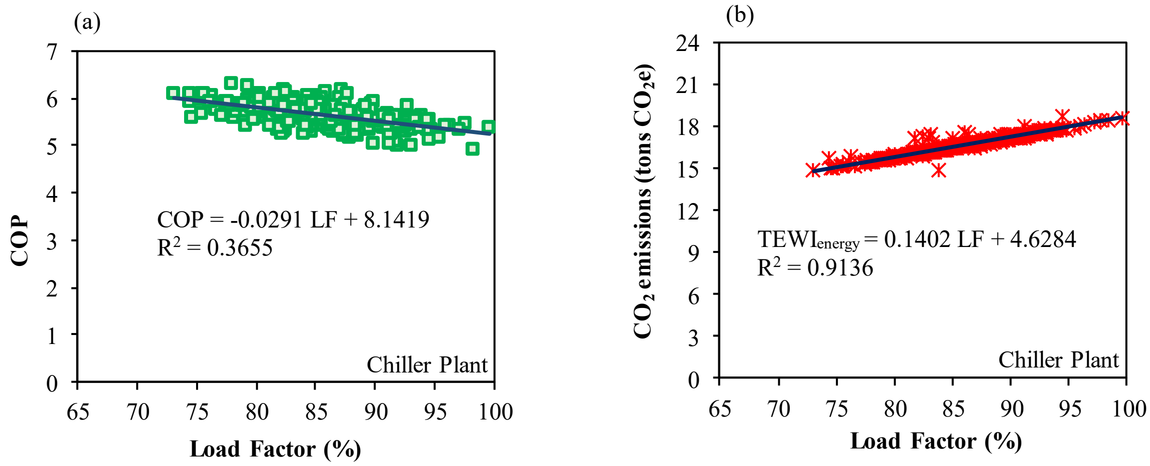

FIGURE 10. Regression analysis the effects of load factor (LF) on: (a) the COP and (b) CO_2 emissions

Energy Profile and Energy Use Intensity of the Supermall

For energy conservation purposes, energy consumption profile of the shopping mall is also presented as can be seen in Table 1. The energy consumption profile categorized based on the service facilities. Annual energy consumption of the whole facilities could reach 27,594 MWh. Air conditioning system is responsible for about 26.1% of total energy use. Large portion of energy consumption is also used for lighting. Energy use intensity (EUI) is found to be 459.89 kWh.m^{-2}.y^{-1}. The EUI was calculated based on gross floor area of 60,000 m^2. This is in agreement with the study reported in [7], for supermall comprises mixture of food and non-food retail stores.

TABLE 1. Energy use of the mall categorized based on services

No.	Services Category	Annual Energy Use (kWh)	Percentage (%)
1	Water Cooled Chillers System	5,129,562	18.6
2	Pumping and Fan Systems for chillers	2,059,473	7.5
3	Public area: lift, lightings, fire hydrant, water supply systems	6,375,796	23.1
4	Mall-1: lighting and small power	6,481,235	23.5
5	Mall-2: lighting and small power	7,547,595	27.4
	Total	**27,593,661**	

CONCLUSIONS

The electricity consumption characteristics of fully air conditioned shopping mall in Indonesia as a tropical country was investigated. The daily energy consumption and environmental impact of the chiller plant was found to be relatively steady all year round with annual energy consumption of the chiller plant was 7,158 MWh corresponding to 6,039 tons CO_2e emissions. Annual Coefficient of Performance (COP) and Coefficient of Performance System (COPS) were 5.64 and 4.11 respectively. The chiller plant was found to operate at overall efficiency of about 0.62 $kW.TR^{-1}$ which was higher than specification of 0.56 $kW.TR^{-1}$. This indicated the chiller plant consumed more energy per ton refrigeration cooling delivered to the building compared with the specification. Further operational optimization on the chiller plant is needed. The study also showed that energy consumption and environmental impact of the chillers were significantly influenced by load factor with a strong positive correlation. Power consumption and CO_2 emissions of the chiller plant substantially increase with the load factor. Monitoring and keeping load factor in the range of 70% to 85% was found to be potential strategies to bring the chillers' efficiency back close to their specification and accordingly for energy efficiency as well as CO_2 emissions reduction of the shopping mall building.

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