

## Increasing performance of chiller systems in high-rise buildings by load optimization

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### ABSTRACT

Recently, the construction of high-rise buildings has been increasing significantly along with economic growth. Therefore, electricity is also going up due to the energy demand of the building. The air conditioning system is the enormous energy consumption in high buildings. The green building concept has been introduced regarding the energy efficiency of a high-rise building. This study investigated the energy consumption in a high building (47 floors) using the load optimization method for the chiller system. The load optimization was conducted by configuring five chillers systems consisting of integral compressors, cooling towers, and pumps. This study obtained the decreasing energy consumption by the chiller's operation load sequencing based on 24-hour data optimization. Optimized chiller performance satisfied the green building standards. However, load optimization on high buildings is highly recommended as an effective way to achieve green building status. Further research is recommended for implementing such optimization at other facilities, such as industrial plants, hospitals, airports, and manufacturing plants.

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## 1. INTRODUCTION

Large city worldwide has seen a steady increase in energy consumption in recent years. Jakarta, the capital city of Indonesia, electricity consumption has risen significantly due to its growing population and increasing industrial and commercial activity. According to data, the city's electricity consumption increased by 6% annually between 2017 and 2019 [1]. In 2017, the total electricity consumption in Jakarta was approximately 28 TWh, equivalent to the energy consumption of a country like Bangladesh [2]. Most of Jakarta's electricity is generated by coal-fired power plants, but a significant amount of electricity is generated from natural gas and renewable energy sources such as hydro and geothermal [3]. In recent years, the government of Jakarta has made efforts to increase the use of renewable energy sources and reduce the city's dependence on fossil fuels. Improving energy efficiency may reduce carbon emissions in numerous sectors. In 2030, there will be an emissions reduction of 3.37 million metric tons of CO<sub>2</sub> if all new buildings in Jakarta improve their energy efficiency system [4]. Therefore, energy consumption should be managed appropriately to achieve optimum efficiency. Instead of the industrial and transportation sectors, the property sector, especially high-rise buildings, is one of Indonesia's most significant energy users. The high-rise building energy is dominated by operating utilities, such as lighting, elevator, escalator, water pump, and air conditioning [5], [6].

Air conditioning and chillers significantly contribute to a building's energy consumption, particularly during peak demand [7]. They typically consume a significant amount of electricity to operate and can strain the electricity grid, particularly in areas with high population density or many buildings with air conditioning systems [8]. This can lead to increased costs for the building owner and potential power outages or brownouts for the community. The air conditioning system is approximately 60% of the requirements [9]. International finance corporation (IFC) has studied to simulate the energy consumption that shows increasing the average temperature regulation to 20°C can save up to 11% of the total energy buildings in Jakarta [4]. The increasing efficiency of air conditioning provides energy-saving opportunities [10]. Nowadays, the operation of a chiller plant significantly reduces energy consumption in buildings. Chiller plants are designed with different unit capacities to adjust the cooling load [11].

Many researchers have studied the chiller system. El Berry proposed a novel method of minimizing the power consumption of a chiller [12]. The study predicted the model and investigated the optimum operating variables of the chiller system by comparing several models. El Berry proposed back propagation artificial neural network (BP-ANN) as the proper model for predicting the coefficient of performance (COP) of the chiller accurately. Then, it was optimized by a genetic algorithm (GA) based to find the optimum solution to obtain the minimum power consumption of the chiller. Wang and Meng *et al.* investigated the experimental and numerical optimization of chilled water configuration to provide better cooling performance and reduce energy consumption [13]. Huang and Zuo proposed a new method for optimizing chiller sequencing control [14]. They implemented model predictive control (MPC) framework, which saves about 5.6% annual energy compared to conventional cooling load-based chiller sequencing control.

Moreover, to reduce the impact, some methods, like using efficient chillers, regular maintenance, smart thermostats, and optimizing the building's heating, ventilation, and air conditioning (HVAC) system to match the occupancy and use patterns better, can help reduce energy consumption [15]. Based on the above references and identifying a chiller plant is essential to save energy consumption during average load and peak load by optimizing the performance of the chiller plant, which is related to increasing the performance of the air conditioning system. The optimization method will be conducted by operating a sequencing chiller system based on flow rate. The paper offers a clear problem statement, proposes a load optimization method for the chiller system, and presents results that demonstrate the achieved energy efficiency and adherence to green building standards. The research presents novel insights and recommends further exploration of load optimization in various other facilities.

## 2. METHODOLOGY

The Standard Green Mark Classification is a rating system developed by the building and construction authority (BCA) in Singapore to evaluate the environmental impact of buildings and promote sustainable design and construction practices [16]. The certification process involves applying and going through pre-assessment, assessment, and verification stages [17]. Buildings that meet the criteria for the certification receive a rating ranging from green mark certified to green mark platinum [16].

According to a study by Huang *et al.* [18], implementing the Green Mark Certification scheme has led to significant improvements in the sustainability of buildings in Singapore. The study analysed the energy consumption and carbon emissions of Green Mark-certified buildings and found that they consumed 20-30% less energy and emitted 20-30% less carbon than non-certified buildings [18]. The study also found that implementing energy-efficient technologies such as LED lighting, efficient HVAC systems, and building automation systems was the most effective way to reduce energy consumption and carbon emissions in buildings [19]–[21].

Another study by Tong *et al.* [21] investigated the factors influencing the adoption of the Green Mark Certification Scheme by building owners and developers. The study found that the most significant factors were the potential cost savings from energy efficiency, the positive effects on creating value and corporate image, and the government's incentives and regulations. However, the study also found that building owners and developers faced barriers such as a need for more awareness and expertise and perceived high costs in implementing sustainable design and construction practices [21]. Addressing these barriers and incentivizing building owners and developers to adopt sustainable design and construction practices is essential to optimizing the Standard Green Mark Classification. One approach is providing financial incentives such as tax credits or grants for buildings with higher certification levels. Another approach is to increase public awareness and education about the benefits of sustainable design and construction practices and the Green Mark Certification Scheme [22].

The Standard Green Mark Classification is a valuable tool for promoting sustainable design and construction practices and reducing the environmental impact of buildings. Implementing the Green Mark Certification Scheme has led to significant improvements in the sustainability of buildings in Singapore,

including reduced energy consumption and carbon emissions [23]. However, to optimize the Standard Green Mark Classification, it is essential to incentivize building owners and developers to adopt sustainable design and construction practices and address barriers such as lack of awareness and perceived high costs.

A chiller system is a mechanical device that removes heat from a liquid via a vapor-compression or absorption refrigeration cycle. This cooled liquid is then circulated through a heat exchanger or chiller coil, to remove heat from a process or space. Typical chiller applications include air conditioning, process cooling, and refrigeration [24]. Chillers can be powered by electricity, natural gas, or steam, and can be designed for refrigerants such as Freon and ammonia [25]. A chiller system is a heat exchanger device that centrally cools the rooms in multi-stores or high-rise buildings. The cooled water is delivered into the rooms so that by using a heat exchanger close to the room, the air will be cooled by the cold water. The water returns to the chiller, then refrigerated by the refrigerant. A cooling tower cools hot refrigerant through a cooling system [26], [27]. The chiller system mechanism is shown in Figure 1.

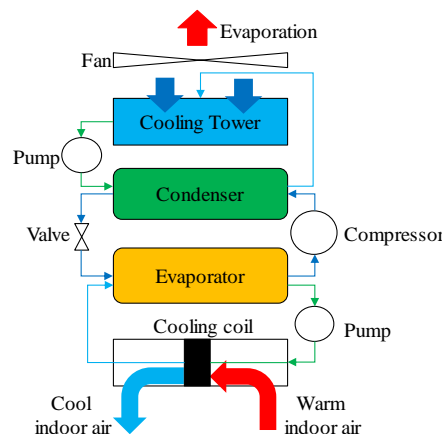


Figure 1. Chiller system scheme using cooling tower

The primary objective of this study is to reduce the power consumption of the chiller system and improve the building's environmental standards to green building classes in the platinum class. As a part of the government's initiative on high-rise buildings, such as hotels, apartments, or office buildings, green building has put forward the concept of saving energy consumption [28]. The government aims to reduce operating costs by reducing electricity consumption in the cooling system or fuel consumption for power generation inside the building. This initiative is because almost 60% of the energy in a building is used for air conditioning. Table 1 displays the Standard Green Mark Classification rating, which provides a framework for assessing the environmental performance of buildings. The Standard Green Mark Classification rating is a crucial indicator of a building's energy efficiency and environmental sustainability. A higher Standard Green Mark classification rating ensures that a building is energy-efficient, environmentally sustainable, and cost-effective.

Table 1. Green mark standard [29]

Green mark rating	Building cooling load (TR)	
	< 500	≥ 500
Efficiency (kW/TR)		
Certified	0.8	0.75
Gold	0.75	0.70
Gold plus	0.7	0.68
Platinum	0.68	0.65

By reducing power consumption in the chiller system, the building can achieve a higher Green Mark rating and become a green building. The goal is to create sustainable and energy-efficient buildings that are environmentally friendly, cost-effective, and comfortable to live or work in. The initiative to reduce power consumption in the chiller system is a significant step in this direction, and it can lead to substantial benefits, including reduced energy consumption, lower operating costs, and a more sustainable environment.

The paper will explain how to reduce power consumption in the chiller system and improve the building's environmental standards to green building classes in the platinum class. The government's

initiative on green buildings is a crucial step in the direction of creating sustainable and energy-efficient buildings that are environmentally friendly, cost-effective, and comfortable to live or work in. A higher Green Mark rating can ensure that a building is energy-efficient, environmentally sustainable, and cost-effective.

This study was conducted using one-month data collection at an office building that has 47 floors and is in Central Jakarta. The building has a chiller system comprising five units, 3 large and two small chillers. The collected data for 24 hours was used as an essential reference for the study. Then, some changes in the operating configuration were proposed to get an optimum result in total energy consumption. They are optimizing chiller sequencing with flow rate and temperature as a basis for cooling load calculations. This methodology is started by identifying the equipment specifications, determining the scheme of the chiller system, observing the energy consumption, optimizing the system's configuration, and comparing the optimum energy consumption of the chiller to Green Mark Standard (Green Building). The following existing chiller system as in Table 2.

Table 2. Specification of the existing chiller system

Chiller	Qty	Cooling capacity	Evaporator flow rate	Evaporator temperature		Condenser flow rate	Condenser temperature	
				in	out		in	out
Large	3	3720 kW/1060 TR	148.3 l/s	14°C	8°C	189.31 l/s	29.5°C	35°C
Small	2	1860 Kw/530 TR	74.2 l/s	14°C	8°C	94.7 l/s	29.5°C	35°C

### 3. RESULTS AND DISCUSSION

#### 3.1. Calculation of chiller system

The performance of the compressor can be obtained by (1) [27], where:

- $W_c$  : Compressor power (kW)  
 $m_f$  : Flow rate of refrigerant (kg/s)  
 $h_1$  : Enthalpy refrigerant compressor input (kJ/kg)  
 $h_2$  : Enthalpy compressor refrigerant output (kJ/kg)

$$W_c = m_f \times (h_2 - h_1) \quad (1)$$

The condenser transfers heat from the refrigerant to water in a chiller system. By rejecting heat, the gaseous refrigerant condenses to the liquid inside the condenser. The heat of condenser output is calculated by (2), where:

- $Q_{cond}$  : Heat of condenser output (kW)  
 $m_f$  : Refrigerant mass flow rate (kg/s)  
 $h_{in cond}$  : Enthalpy of refrigerant at condenser input (kJ/kg)  
 $h_{out cond}$  : Enthalpy of refrigerant at condenser output (kJ/kg)

$$Q_{cond} = m_f \times (h_{in cond} - h_{out cond}) \quad (2)$$

Flow rates on the water condenser system can be calculated using (3), where:

- $Q$  : Flow rate of water condenser (kg/s)  
 $q_0$  : Heat rejection (kW)  
 $\rho$  : Density of water (kg/m<sup>3</sup>)  
 $t_1$  : Temperature of water at condenser inlet (°C)  
 $t_2$  : Water temperature at condenser outlet (°C)  
 $C_p$  : Specific heat capacity (kJ/kg.K)

$$Q = \frac{q_0}{\rho \times c_p \times (t_2 - t_1)} \quad (3)$$

Evaporator capacity is the ability of the evaporator to absorb heat in a certain period and is determined by the difference in evaporator temperature [30]. The ability to transfer heat can be calculated by (4), where:

- $Q_{evap}$  : Heat of the evaporator output (kW)  
 $m_f$  : Refrigerant mass flow rate (kg/s)  
 $h_{in evap}$  : Enthalpy of refrigerant at evaporator input (kJ/kg)  
 $h_{out evap}$  : Enthalpy of evaporator at refrigerant output (kJ/kg)

$$Q_{evap} = m_f \times (h_{in\ evap} - h_{out\ evap}) \quad (4)$$

In the refrigeration system, the amount of heat the refrigerant takes in the evaporator from the environment will be proportional to the enthalpy between the input and output. The effects of refrigerant or  $q_E$  as (5), where:

$q_E$  : Refrigeration effect (kJ/kg)  
 $h_{in\ evap}$  : Enthalpy of refrigerant at evaporator input (kJ/kg)  
 $h_{out\ evap}$  : Enthalpy of refrigerant at evaporator output (kJ/kg)

$$q_E = (h_{in\ evap} - h_{out\ evap}) \quad (5)$$

The chiller sequencing control system is needed to turn on and turn off the chiller to match the cooling demand and cooling load. It intends to achieve energy savings in air conditioning systems [31]. To achieve high efficiency, some researchers build optimization based on adjusting each chiller's partial load ratio (PLR) according to the cooling load [14]. The coefficient of performance (COP) can be sought by calculating the chiller energy consumption and cooling load capacity. Plant chiller performance will be efficient if several components (chilled pump and condenser pump) are also efficient [32]. The formulation for COP is as (6).

$$COP = \frac{\text{Energy utilized}}{\text{Energy used as work}} \quad (6)$$

### 3.2. Chiller water cooling load sequencing

Sequencing a chiller or staging chiller is one method to determine the work of the chiller, which is generated by the cooling load demand. The chilled water pump is one of the chiller plant components to pump chilled water in a closed system [33]. The refrigerant is expected to be in a liquid phase to absorb heat from the water. The identification results will determine the operating chillers and the standby chillers. In Figure 2, the flow chart is used to operate the chilled water pump, condenser pump, and cooling tower cell.

Table 3 shows the chilled water pump sequencing based on the chilled water flow rate. The configuration combines small-large pump configuration from low to high load demand. The designation of 1S is one small pump, 1L is one large pump, 1S + 1L is a combination of one small pump and one large pump. The pump load is represented by the litre/second (l/s) unit flow rate. Due to a technical reliability reason, determining pump operation is based on 75% of the installed chilled water pump capacity.

Table 3. Chilled water pump sequencing diagram

Configuration of chilled water pump load sequencing (l/s)							
1S	1L	1S + 1L	2L	1S + 2L	3L	1S + 3L	2S+3L
0-70	71-119	120-161	162-211	212-250	251-300	301-344	>345

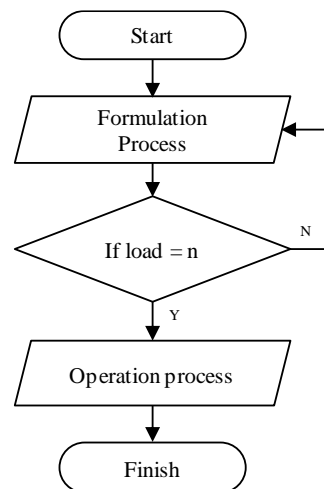


Figure 2. The flow chart for the operation process

### 3.3. Condenser water pump load sequencing

Condenser water pump staging is one method to determine pump work generated by cooling load demand. As shown in Table 4, condenser water pump control is based on the flow rate in the cooling load demand, and then it will be used to determine when the pumps are in operating or standby mode—the sequence of the condenser water pump based on the identified flow rate. The pump work is also based on 75% of the installed capacity. The sequence water pump condenser scheme is shown in Figure 2. The control of pumps is carried out from a minimum load demand by operating a small pump to the maximum load sequentially following the capacity of each pump.

Table 1. Condenser water pump sequencing diagram

Configuration of chilled water pump load sequencing (l/s)							
1S	1L	1S + 1L	2L	1S + 2L	3L	1S + 3L	2S+3L
0-72	73-136	137-189	190-250	151-303	304-367	368-422	>423

### 3.4. Cooling tower cell load sequencing

Cooling tower cell load sequencing is a technique used to determine the working of a cooling tower cell. The cooling tower cell is an essential component of the cooling system in a building, and its efficient operation is critical to ensure optimal cooling performance. The fans in the cooling tower cell generate work based on the cooling load demand. The fans take hot air from the building and pass it through the cooling tower cell. Heat is transferred from the perspective to the water in the cooling tower, and the cooled air is returned to the building. If the heat is taken from the air, then the air will be in contact with objects or materials at lower temperatures [34].

For optimal operation of the cooling tower cell, it is essential to determine when the fans are in process and when they are in standby mode. This information can be used to adjust the cooling load demand and ensure that the cooling tower cell operates optimally. In the present study, the condenser water flow rate in the cooling load demand was used to determine the work of the cooling tower cell. The cooling tower cell sequencing schemes are shown in Table 5, and they provide a framework for optimizing the operation of the cooling tower cell.

Using the cooling tower cell sequencing schemes, the facility management team can ensure that the cell is operating efficiently and meeting the cooling load demand. This can help reduce energy consumption and associated costs, improve the building's indoor air quality, and extend the cooling system's lifespan. Overall, cooling tower cell load sequencing is a valuable tool for optimizing the operation of cooling systems, and its implementation can lead to significant benefits in terms of energy efficiency, cost savings, and sustainable building operation.

Table 2. Cooling tower cell sequencing diagram

Configuration of cooling tower cell load sequencing (l/s)							
1 cell	2 cell	3 cell	4 cell	5 cell	6 cell	7 cell	8 cell
0-100	101-150	151-200	201-250	251-300	301-350	351-400	>400

## 4. RESULT AND DISCUSSION

The above parameters and methodology were used in this study to evaluate the performance of a chiller system. This study's result parameter of interest is expressed in kW/TR, which measures the chiller system's performance. This value was obtained by monitoring data on the building management system (BMS) for 24 hours, providing an overall performance value for the chiller plant daily. The data collected was then formulated to define the load demand, which was subsequently used to optimize the efficiency of the chiller plant. To better understand the performance of the chiller system, Figure 3 displays the cooling load curve at the building for 24 hours. This curve illustrates the cooling load demand at different times of the day, which can be used to optimize the chiller plant's operation to meet the energy demand efficiently. The data collected through this study can be used to identify areas for improvement in the chiller plant's performance, ultimately leading to the optimization of energy usage and reduction in energy costs.

Furthermore, the results of this study can be used to validate the chiller plant's energy efficiency and compliance with energy standards. By monitoring the chiller plant's performance in real time, the facility management team can identify and address issues promptly, ensuring optimal operation to meet the building's cooling demand. In summary, this study demonstrates the importance of monitoring and optimizing the performance of chiller plants to achieve energy-efficient and cost-effective operation.

Figure 3 shows the 24-hour cooling load curve at low and peak loads. Low load occurred between 01:00 and 04:00, reaching around 377.37 kW. Between 06:00 to 18:00 is the peak load, where the cooling demand increases from around 4612.91 to 4608.53 kW. From 19:00 to 0:00, the need for cooling decreases to 504.47 kW at 0:00. Table 6 shows the configuration of each chilling equipment in an hour of essential operation as an optimization result. That CHWP is a chilled water pump, CDWP is a condenser water pump, and CT is a cooling tower.

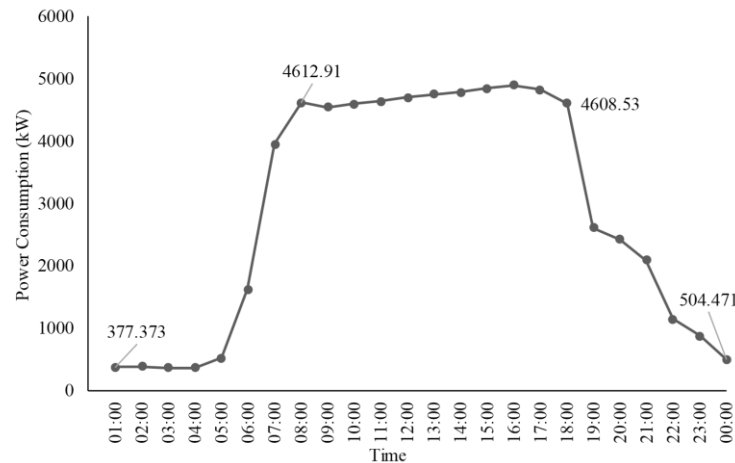


Figure 1. Cooling load curve (kW)

For example, at 01:00, the chiller system utilizes one small-chilled water pump (1S), one small condenser water pump (1S), and one cooling tower cell. This configuration is based on the demand of the cooling load. On the other hand, in the peak hour, the chiller system utilizes two large-chilled water pumps (2L) and two large condenser water pumps (2L), and seven cooling tower cells.

Table 3. Chiller system sequence and configuration in 24 hours operation

Time	CHWP	CDWP	CT	Time	CHWP	CDWP	CT
01:00	1S	-	1S	13:00	-	2L	-
02:00	1S	-	1S	14:00	-	2L	-
03:00	1S	-	1S	15:00	-	2L	-
04:00	1S	-	1S	16:00	-	2L	-
05:00	1S	-	1S	17:00	-	2L	-
06:00	1S	-	0	18:00	-	2L	-
07:00	-	2L	0	19:00	1S	1L	1S
08:00	-	2L	0	20:00	1S	1L	1S
09:00	-	2L	0	21:00	2S	-	1S
10:00	-	2L	0	22:00	1S	-	1S
11:00	-	2L	0	23:00	1S	-	1S
12:00	-	2L	0	00:00	1S	-	1S

Using the equation in section 3 and implementing the sequence configuration in Table 4 describes a process in which an equation from section 3 was used, and a sequence configuration provided in Table 4 was implemented to generate the total chiller plant power curve for 24 hours of operation. Figure 4 displays the resulting power curve. The figure shows that the chiller plant's power consumption is highest between 07:00 and 18:00, with an average load consumption of approximately 772 kW. This information can be used to optimize the chiller plant's operation and reduce its energy consumption during the high load period. Additionally, the power curve can aid in predicting energy consumption and planning energy management strategies, ultimately lowering energy costs, and contributing to a more sustainable operation.

In addition, Figure 5, presented in this sentence, is a graphical representation of the performance of a chiller plant in terms of kW/TR compared to the Green Mark Standard. The curve in the graph represents the plant's performance during different time intervals. For example, the value of 0.87 kW/TR, which is above the Green Mark Standard, indicates that the chiller plant was operating efficiently during the period from 01:00 to 05:00. However, the performance of the plant from 07:00 to 23:00 was below the Green Mark Standard, with a

value of less than 0.68 kW/TR. This suggests that the chiller plant was not operating optimally during this period, and there may be several reasons, including inefficiencies in the system or external factors affecting its operation. This information can help identify areas for improvement in the chiller plant's performance to ensure it is operating at its maximum efficiency and meeting the Green Mark Standard.

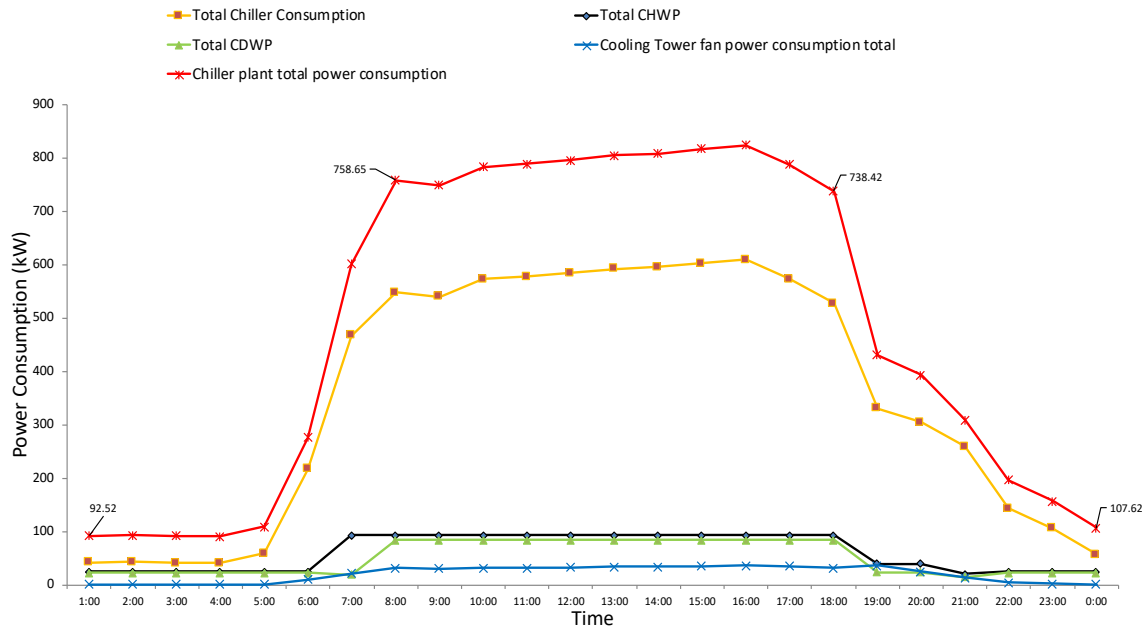


Figure 2. Chiller plant power curve (kW)

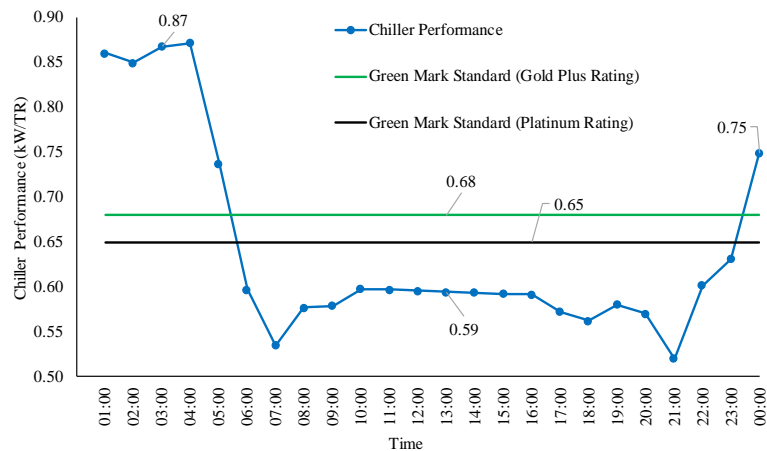


Figure 3. Chiller plant performance (kW/TR)

## 5. CONCLUSION

This study successfully proved that the load sequencing optimization of the chiller system could reduce electricity consumption at a high-rise building. At low loads between 00:00 and 04:00, the chiller plant performance yields the green building standard (more than 0.68 kW/TR). However, at the peak load between 07:00 to 18:00, the chiller plant performance achieved the requirement of the green building standard (less than 0.68 kW/TR), which is categorized as a platinum class. The efficiency of the chiller plant is affected by the optimization of the chiller, pumps, and cooling tower fans configuration. Further research is suggested to investigate the effect of load optimization for other building types, such as industrial plants, hospitals, airports, and manufacturing plants.

Optimizing chiller systems is an essential strategy for reducing energy consumption and increasing the sustainability of high-rise buildings. This study provides valuable insights into the load sequencing



optimization of chiller systems and its impact on electricity consumption in high-rise buildings. The results of this study demonstrate that load sequencing optimization can significantly reduce electricity consumption in high-rise buildings.

The study found that at low load between 00:00 and 04:00, the chiller plant performance yielded the green building standard, with an efficiency of more than 0.68 kW/TR. However, at peak load between 07:00 to 18:00, the chiller plant performance achieved the requirement of the green building standard, with an efficiency of less than 0.68 kW/TR, which is categorized as a platinum class. Optimizing the chiller, pumps, and cooling tower fans configuration affected the efficiency of the chiller plant, highlighting the importance of careful design and configuration of chiller systems in high-rise buildings. The findings of this study have significant implications for the design and operation of chiller systems in high-rise buildings. By optimizing the configuration of chiller systems, building owners and managers can significantly reduce energy consumption and operating costs while improving the sustainability of high-rise buildings. The results of this study also suggest that load optimization can be effective in other types of facilities, such as industrial plants, hospitals, airports, and manufacturing plants.

Further research is needed to investigate the effect of load optimization on other types of buildings and to develop more advanced optimization strategies for chiller systems. Integrating advanced control systems, machine learning, and artificial intelligence could significantly improve the efficiency of chiller systems and reduce energy consumption in high-rise buildings. Overall, the findings of this study demonstrate the importance of load sequencing optimization in reducing energy consumption in high-rise buildings and highlight the need for continued research and innovation in sustainable building design and construction practices.

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