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Investigation of the impact of building orientation on cooling loads in an office building in the tropical climate

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Abstract

The building sector ranks second behind the fossil fuel burning industry. This figure may significantly rise when the total number of buildings and cooling demands increases, as well as poor HVAC system usage.

In tropical climates such as Indonesia, building energy consumption is dominated by cooling loads on air conditioners to reduce indoor temperatures. This study focuses on the orientation of buildings in tropical climates on the amount of cooling load in a mid-rise rental office tower: WTC 5 in Jakarta. Several Energy Plus simulations utilising real building characteristics were performed to assess the impact and capacity of cooling loads on various building levels. The current 45°N building is turned clockwise, and cooling demands are computed and compared.

The evidence found from simulations in five building scenarios shows several data on each building floor. The south-oriented building can maximise the lowest cooling load of 7.47 kWh, which is quite far from the existing building and the east-west orientation is 7.72 kWh and 7.80 kWh at the same time. The resulting curve can be interpreted that the orientation of the building has an enormous impact in terms of the effect of cooling loads on buildings, especially in tropical climates.

Keywords: building orientation, building performance, cooling loads, tropical climate

1. Introduction

Buildings are quickly expanding throughout the globe, accounting for 38% of all CO_2 emissions [1], resulting in negative environmental effects such as global warming, climate change, greenhouse gases, air, urban heat island, and water pollutants, and fossil fuel usage. The Intergovernmental Panel on Climate Change (IPCC) [2] reported in its Fifth Assessment Report (AR5) that there has been a nearly 30 per cent increase in CO_2 in the atmosphere since the industrial revolution as a result of burning fossil fuels and illegal deforestation [3]. Other reasons, according to the IPPC, include world buildings in the metropolitan region, which accounted for 32 per cent of global final building energy consumption in 2010 [4]. Building energy consumption is caused by the heating and cooling of structures. As a result, by 2050, this may treble or perhaps quadruple [5]

To optimise building energy performance, studies on factors considered capable of reducing energy consumption are significant. Several studies have separated these factors into internal and external factors [6]–[9]. Climate conditions in a zone are the most critical external element, as seen by variances in sun path diagrams, psychrometric charts, and wind roses for each location. Humidity, exterior temperature, solar radiation, wind velocity, and wind direction are examples of external variables, whereas HVAC systems, materials and structures, equipment, and illumination are examples of internal factors. Internal aspects mainly refer to the building settings, including building orientation, building form and envelop.

1.1. Building Orientation and Climate

Solar energy access is a crucial factor affecting any building's energy performance. It varies with the seasons in a given geographic location; thus, it is necessary to heat or cool the building within the range of the available solar energy in different directions [10].

The Köppen climate sorting system (shown in Fig. 1), which is one of the most widely used methods for evaluating a location's climate, will be performed to examine building thermal efficiency later.

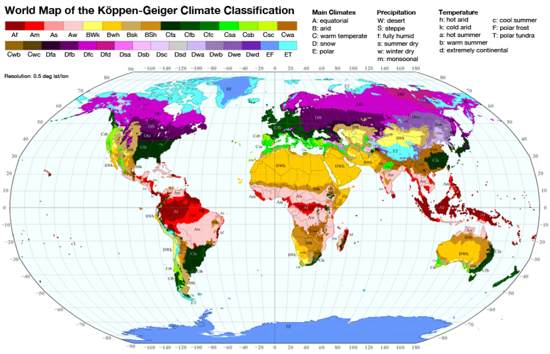


Figure 1. World map of the Köppen-Geiger Climate Classification[11]

The Köppen classification splits into five distinct climate zones. A tropical climate, B a dry climate, C a mild temperate climate, D a snowy climate, and E a polar climate. Variances in climate across the globe as a consequence of solar energy also affect differences in solar radiation acquisition in a variety of climatic zones.

This study will focus on a building in a tropical climatic region near the equator, where it is hot, humid, and wet all year. As a result, it has a lot of solar energy potential [12]. Tropical nations are usually found around or on the equator line. Every year, the main climatic condition is wet and dry, with high humidity and almost equal daytime and nighttime temperatures.

Firrbudi [13] outlines three major strategies for maximising building performance in tropical climates. To begin, the sun is faced by the building orientation, which is ideal for a building facing north-south with east-west facades. Mistakes in calculating the orientation will cause the building to overheat, similar to an oven—second, the use of the skylight from the window parameter will cause the structure to overheat. Finally, in the building respiration system, a natural ventilation system channels out hot air and channel in cold air.

In the points above, Shao et al. [14] similarly agreed that the building orientation factor is a determining factor in the thermal performance of the building.

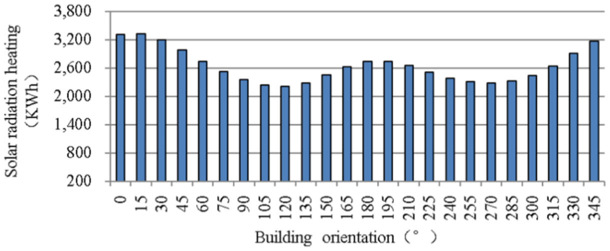


Figure 2. Solar radiation heating of different building orientation [14]

After simulating a residential house in the cold region of China, the difference in solar radiation heating is striking at 1,200 kWh (see Fig. 2) at building orientations of 15°N and 120°N. Curve changes often arise when the building rotates from north to south, demonstrating the influence of building orientation on heat gain.

1.2. Energy Consumption of The Commercial Building in The Tropical Climate

HVAC systems, heating, ventilation, and air conditioning, which provide 35 percent of total building energy yearly, are followed by electronic equipment, lighting, and others, which each contribute less than 20 percent [15]. According to Santamouris [16], the heating and cooling load in public buildings such as offices, hotels, and hospitals may account for up to a third of the total energy usage. Heating and cooling loads in the HVAC system account for the majority of annual building energy consumption.

Table 1. Artificial lighting use as a proportion of total energy consumption in various buildings [16]

Type of Building	Share of end-use for lighting (per cent)
Commercial buildings	50 %
Residential buildings	10 %
Schools	10 % - 15 %
Factories	15 %
Hospitals	20 % - 30%

As given away in Table 1 displays, the use of electricity in commercial buildings far exceeds other buildings such as schools, factories, and hospitals. The data displayed are many buildings in Germany that are categorised into warm and temperate climates.

Meanwhile, in tropical climate regions such as South East (SE) Asia, Malaysia and Indonesia, concern about building energy consumption has been raised. Buildings account for a huge amount of total electricity, and energy consumption constantly augmented due to subsidised electricity, residents growing and economic prosperity. By 2020, the energy consumption in SE Asia countries will exceed that of developed countries. Figure 3 displays representative building energy consumption in SE Asia [17]. In Fig. 3, it can be seen that even in buildings in tropical climates, the percentage of HVAC still dominates the energy use of the building as a whole.

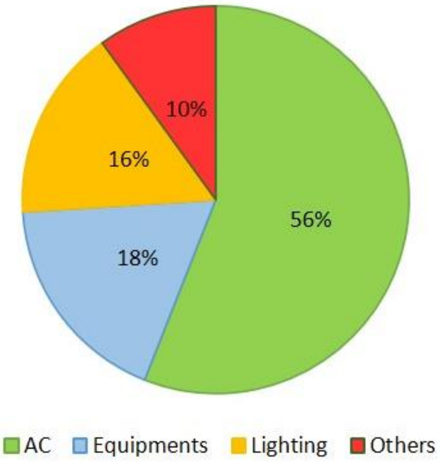


Figure 3. Characteristic Building Energy Consumption in Tropical Climate [17]

Katili [15] describes this number as widely used for the cooling process of buildings to keep building occupants in their comfort zone. As a result, a wise solution is required that does not immediately involve the usage of air conditioning to reduce the room's temperature.

1.3. Calculation of Heating and Cooling Loads

Understanding the thermal characteristics of building components such as walls, roofs, windows, and floors is critical for estimating the heating and cooling load on the HVAC system and achieving thermal comfort. The heating load is the total amount of heat energy that must be put in the area to keep the temperature within an acceptable range.

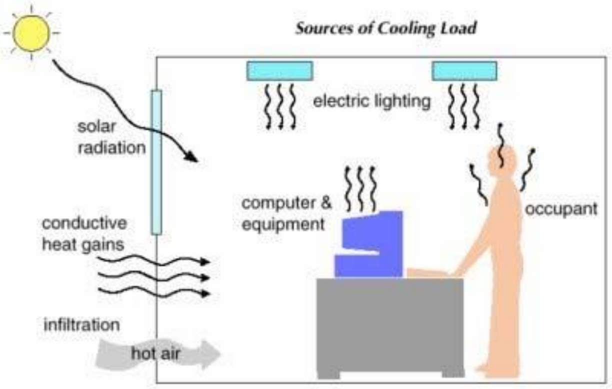


Figure 4. Sources of Cooling Load [18]

Cooling load, on the other hand (see Fig. 4) refers to the quantity of thermal energy that must be evacuated from a space to keep the temperature within a safe range.

Three techniques for calculating zones and whole-building loads are extensively described in the ASHRAE Handbook Fundamentals, 2001 [19]:

a. Transfer Function Method (TFM): This is one of ASHRAE's more difficult techniques, and it necessitates the use of computer software or a spreadsheet.

b. Cooling Load Temperature Differential/Cooling Load Factors (CLTD/CLF): Based on the TFM approach, this strategy uses organised data to reorganise the calculation handle. The approach can be easily transferred into simple spreadsheet applications, although it does have certain limitations owing to the organised data.

c. Total Equivalent Temperature Differential/Time-Averaging (TETD/TA): When I first presented the CLTD/CLF method, this was the ideal strategy for manual or simple spreadsheet calculations.

Although these three approaches have several drawbacks, much prior research has used the first way to create Building Energy Simulation (BES) software with a high degree of accuracy [20], [21].

The purpose of this study is to evaluate the impact of building orientation on medium-rise structures in tropical climatic regions, with the selected site being an office building as one of the commercial buildings in Jakarta, Indonesia's capital city, which is situated near the equator.

Furthermore, the findings of this research will reveal how much energy an office building expends to maintain its inhabitants in a thermally comfortable zone.

2. Method

Starting with a building display and analysing the Building Energy Simulation (BES) devices, this chapter will explain the methods used in deconstructing the warm execution of structures, starting with the history and literature. Its focus is on studying the cooling load of a mid-rise structure in Indonesia, which has a tropical environment. As a result, the study will gather data from the building's ground, middle, and top floors to assess how much energy is used by the cooling system throughout the year. Between June and August 2019, data collection and simulation were conducted at a one-hour interval sandwiched between 08.00 and 17.00 after business hours. On each of the three levels, each surface will be evaluated from various angles: north, east, south, and west, so that a comparison of the total data can be made to determine the optimum cooling load orientation.

2.1. Selection of Building

The cooling load of an office building in Sudirman Central Business District or SCBD in South Jakarta, the Jakarta World Trade Centre, will be investigated in this study. Jakarta is located in the west of Java, with a latitude of 6°12'52.63"S and a longitude of 106°50'42.47"E, with a tropical monsoonal climate.

Figure 5. World Trade Centre Jakarta Complex (www.jakland.com)

Jakarta is divided into two seasons: rainy and dry. The stormy season lasts for most of the year, from October to May, while the dry season lasts for the majority of the year, from June to September. Jakarta's average annual temperature is about 27°C, with a wide temperature range of 24°C to 29.5°C [22]. The tropical storm climate is characterised by average monthly temperatures of above 18°C throughout the year [23].

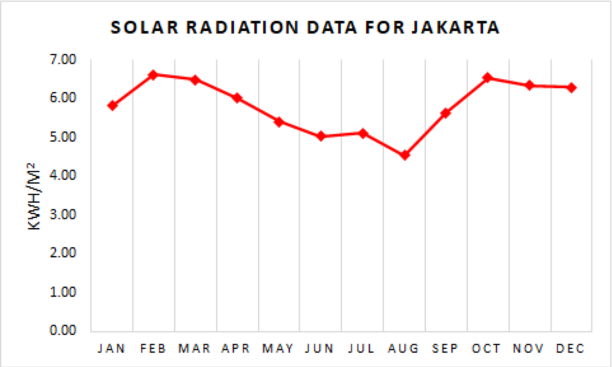


Figure 6. Solar radiation data for Jakarta. Source: Green Building Studio

Meanwhile, data from Autodesk Green Building Studio for a year in Jakarta reveals a reasonably steady trend, although it reached a low of 4.55 kWh/m^2 in August. However, there is a possibility of 5.83 kWh/m^2 that may be reused for energy consumption in buildings on an annual basis. Solar heat, on the other hand, may harm a building's thermal performance, particularly if it is not effectively handled owing to the heat transfer that happens. One of the first steps in preventing excessive heat in the building is to determine the optimal orientation on the sun path diagram.

As seen in Fig. 7, the sun path diagram of Jakarta outlines the picking up of sunshine, which is comparatively the same all through the year, from 06:00 to 18:00. It has more than ten hours of sun-powered from dawn to dusk time since the area of Jakarta is near to the equator. Jakarta experienced an under-heated period between January and March, whereas the overheated period happened from August to October.

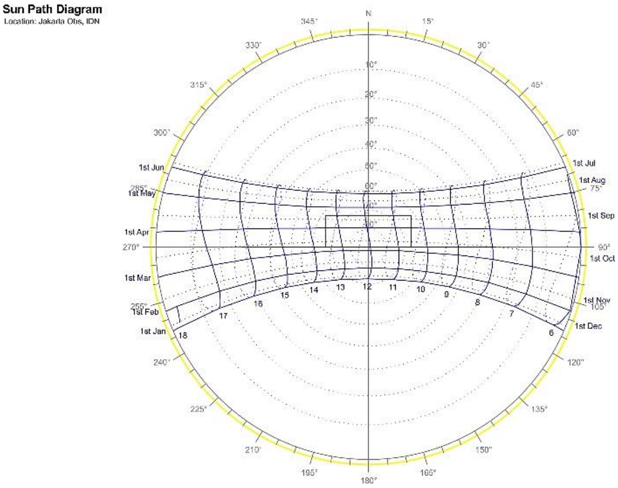


Figure 7. Diagram of the Sun Path in Jakarta. Autodesk's weather tool is the source of this information.

The sun path diagram of Jakarta, as shown in Fig. 7, depicts the collection of sunlight, which is relatively constant throughout the year, from 06:00 to 18:00. Because Jakarta lies close to the equator, it receives more than 10 hours of sunlight from dawn to sunset. Between January and March, Jakarta had an under-heated phase, whereas August to October saw an overheated period.

2.2. Simulation Parameter Settings

To analyse the cooling load of the building, comprehensive building data such as location, weather data, HVAC systems, internal design, and operating schedules are compulsory. Therefore, in this study, several parameters on building elements are adjusted according to actual conditions to obtain an accurate cooling load.

As mentioned by Hashim et al. [24], that parameter value of the thermal performance of buildings improved designed for heating in winter and also cooling in summer is vital for the precision of the design and the suitable optimal of equipment for the adaptation of air and air handling units (AHU) to meet the requirements for the suitable HVAC system, thermal comfort and reasonable distribution of air inside the building.

Table 2. Inputs for the case study [25]

Parameter	Unit
Location	n/a
Orientation	n/a
Building Dimension	m^3
U-value	$W \cdot m^2/K$ $(Btu/h \cdot ft^{2} \cdot °F)$

Heat Gain	W/m^2 (Btu/h·ft^2)
Convective part	n/a
Heating temperature	°C (°F)
Cooling temperature	°C (°F)

The type of window, window-to-wall ratio (WWR), shading device, and solar heat gain control plans, according to Shan [25], have a significant impact on building energy demand, and there is a tremendous opportunity for building facades to reduce energy demand through the modification model, such as type of window, WWR, shading device, and solar heat gain control plans. The techniques of parameter optimization may be categorised as discrete or continuous parameter optimization methods. Because heat passes through the building's outside surface first, continuous parameters are virtually non-existent in façade design, discrete parameters techniques are often employed. Window size, building material, insulation width, and glazing kinds are examples of discrete factors (SHGC, U-value). Building energy performance may be better assessed utilising optimization methods that use discrete parameters and Building Energy Simulation (BES) technologies.

The type of window, window-to-wall proportion (WWR), shading device, and sun-powered warm pick up control plans, according to Shan [25], have a significant effect on building vitality request, and there is a significant possibility for building facade to cut vitality request through the adjustment demonstrate, such as type of window, window-to-wall proportion (WWR), shading device, and sun-powered warm pick up control plans. Discrete or nonstop parameter improvement methods are the two types of enhancement strategies. Because warm, to begin with, via the exterior surface of the building's endless parameters are virtually non-existent in the façade plan, discrete parameters methods are often used for façade plan problems. Window measurements, building fabric, separator width, and coating types are examples of discrete characteristics (SHGC, U-value). Enhancement methods that use discrete parameters in conjunction with Building Energy Simulation (BES) instruments are more practical for analysing building vitality execution.

2.3. Building OrientationSimulation Scenarios

Building modelling started to be redone using Sketch Up and Revit Autodesk, according to the literature. The following criteria were utilised to condition dimensions, volumes, materials, and the surrounding environment based on the present situation:

Table 3. Building Parameter Settings

Items	**Parameter Settings**
Geometric Information	
Ground Floor	1000 m^2
Building Surface	2390 m^2
Exposed Range	390 m^2
Glazing	121.5 m^2
Building Volume	3000 m^2
Occupancy	
Function	Office – typical (12 m^2)
Activity	Sedentary – 70 w
Heat Gains	
Sensible	5 W
Latent	2 W
Air Infiltration	
Air Changes rate	0.5ach
Wind velocity	0.25ach
HVAC System	
Type	Mixed mode system
Maximum Temp	24°C
Min Temp	20°C
Weekday On	07:00
Weekday Off	20:00
Weekend On	00:00
Weekend Off	00:00
Comfort Settings	
Clothing (Clo)	1.0
Air Velocity	0.50 m/s
Lighting category	400 lux
U-Value	
Wall's U-Value	2.62 W/ m^{2}K
Floor's U-Value	2.90 W/ m^{2}K
Window's U-Value	6 W/ m^{2}K
Roof's U-Value	0.89 W/ m^{2}K

Later arranging several parameters above, simulation is accomplish using Energy Plus software on some building floors, namely floors 1, 8, and 15.

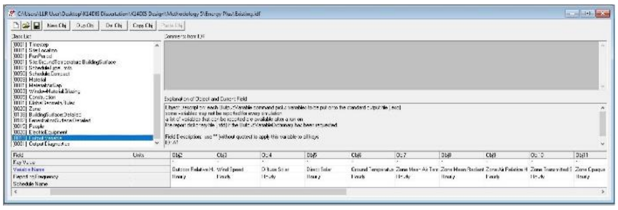
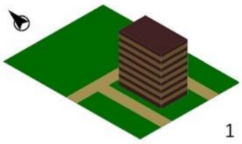
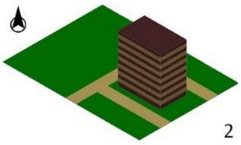
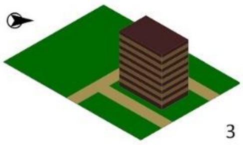
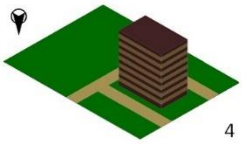
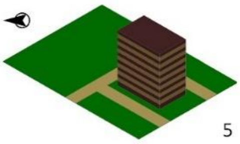


Figure 8. Output variable on energy plus

The thermal performance of WTC 5 will be evaluated in less than 24 hours to estimate the building's cooling demand for a year. A mixed-mode air conditioning system with 20°C to 24°C thermostats was used. On weekdays, the building is open from 7:00 a.m. to 8:00 p.m., and on weekends, it is open from 7:00 a.m. to 8:00 p.m.

Table 4. Building orientation simulations scenarios

Simulation	Orientation	Isometric
Scenario 1: stand-alone building	-45°N	
Scenario 2: rotate the orientation of the building	0°N	
Scenario 3: rotate the orientation of the building	90°N	
Scenario 4: rotate the orientation of the building	180°N	
Scenario 5: rotate the orientation of the building	270°N	

Starting from the present situation, where the building's orientation is -45°N facing southwest, the simulation will go through five phases of scenarios by modelling the facade surface of the building zone. The building turns 15°N toward 0°N in the first scenario. As a result, the long sides of the triangle point east and west, respectively. The main building turns from 105°N to 90°N in the third scenario. The long side is North and South orientated. Later, the structure rotates again, leading to 180°N. Scenario 2's building has the same orientation as Scenario 1. The main entrance, on the other hand, is now facing east. Finally, the structure turns 45°N counter-clockwise, heading 270°N, in the fifth condition.

The research began with Energy Plus simulations based on some of the possibilities in Table 4. As a consequence, the outcomes of each category will be compared to determine the optimal orientation.

3. Results and Discussion

After simulating building energy performance in quite a few orientations for five scenarios, last of all, 180 simulation data found. For the efficiency of the data displayed, this section will only directly compare all of them into several graphs.

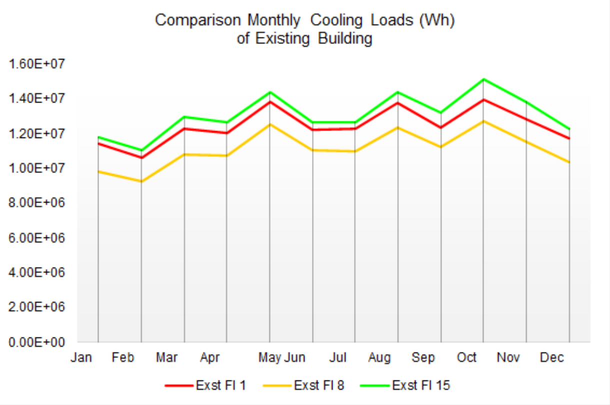


Figure 9. Monthly Cooling Loads Comparison of Existing Buildings in WTC 5, Jakarta

In a preliminary assessment of existing structures in WTC 5 Jakarta, the cooling load on each level, one, eight, and fifteen storeys, looks unstable. The 15th level has the most cooling load, followed by the first and eighth floors. In October, the 15th floor had a high demand of 15.14kWh and a low load of 11.08kWh.

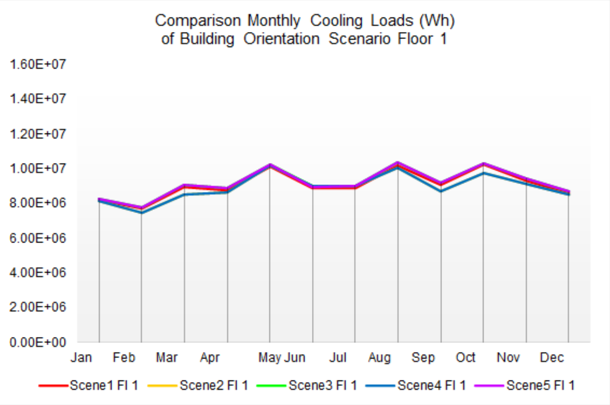


Figure 10. Monthly Cooling Loads in WTC 5 Jakarta for Building Orientation Scenario Floor 1

In Graph 12, it appears that the pattern is similar as shown in the existing building. However, there are differences shown in scenarios 4 and 2 when the building faces 0°N and 180°N, where the cooling load is lower than in other experiments. If averaged over one year, the use of room cooling is 8.64 kWh, which is lower than the other scenarios which touched 13.3 kWh, especially in scenarios 3 and 5.

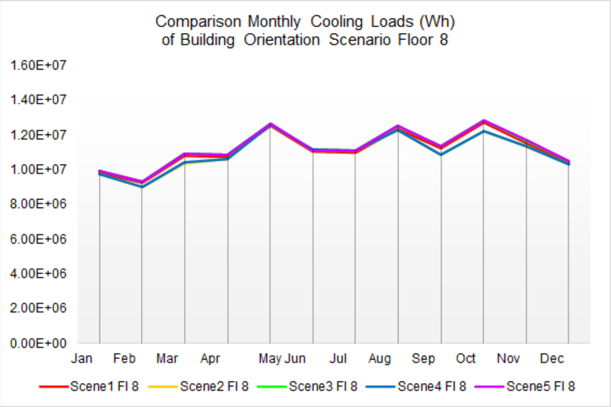


Figure 11. Monthly Cooling Loads in WTC 5 Jakarta for Building Orientation Scenario Floor 8

A similar shape is shown in Graph 13, which compares the monthly cooling load on the 8th floor of WTC 5. The peak cooling load was seen in May and October at 12.7 kWh and 12.8 kWh. In this comparison, again, scenario four can maximise the cooling load seen in February to April and September to November.

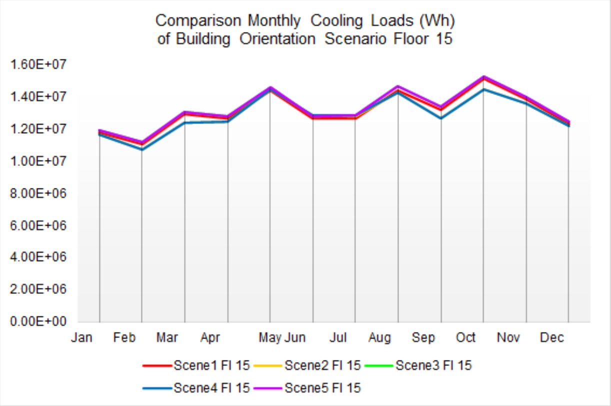


Figure 12. Monthly Cooling Loads in WTC 5 Jakarta for Building Orientation Scenario Floor 1

The 15th floor, as the top floor of WTC 5, uses the highest cooling load compared to the floor below. However, the pattern is shown also looks similar compared to calculations on other floors and existing buildings. Again, the maximum results are shown in scenarios 4 and 2, with an average cooling load of 12.9 kWh in a year.

Building orientation has an influence on energy consumption and building thermal performance, substantially cooling loads in tropical climates, according to field research and numerical simulation.

The best building orientation is facing south-north where in this scenario, the building can control solar radiation so that the incoming heat transfer is not excessive, especially at the peak of summer in May, August and October. While in other scenarios, the longitudinal plane is not anticipated by making appropriate openings and direct solar heat dissipation to minimise heat gain, especially in tropical climate areas.

4. Conclusion

According to the findings of the study, there are many critical things to keep in mind. The first point to note is that the variation in cooling load between scenarios 2 and 4 buildings resulting in 0°N and 180°N, respectively, is considerably lower.

Second, each month's cooling load is different, as shown by each graph. This is comparable to the pattern produced by the solar energy that Jakarta receives throughout the year. As mentioned before, solar radiation in August is the lowest of the year in Jakarta, while the cooling demand is variable in each situation. The cooling load was one of the highest in that month, at 14.7 kWh in scenarios 3 and 5.

The third result indicates that the building's top level has the highest cooling load in comparison to the other floors. As Song and Kim [26] definite that the height of the building affects the quantity of cooling load.

Because their design, structure, function, and behaviours are essential contributors to energy-related sustainability issues, buildings solve a sustainable future. They reduce energy consumption in buildings and play one of the most crucial roles in tackling these challenges. As a result, awareness of energy in buildings is critical, as evidenced by the tests that have been conducted.

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