Comparison of variation in the building shapes and the window-to-wall ratio by concerning energy consumption for thermal comfort and lighting

Andre Kurniawan[1*], Remon Lapisa[1], Muhammad Yasep Setiawan[1], Bulkia Rahim[2], and Budi Syahri[2]

[1] Centre for Energy and Power Electronics Research, Universitas Negeri Padang, Padang, **INDONESIA**
[2] Department of Mechanical Engineering, Faculty of Engineering, Universitas Negeri Padang, Padang, **INDONESIA**

* Corresponding Author: andrekurniawan@ft.unp.ac.id
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Abstract: Currently, an influential factor contributing to thermal comfort home design is the incorporation of energy-efficient passive design principles. It is exemplified by strategic window placement, the utilization of thermally efficient materials, and effective insulation. It exerts a substantial influence on thermal comfort and electrical consumption. This paper examines the effect of building shape and window-to-wall ratio (WWR) on thermal comfort and lighting energy consumption in residential houses in tropical climates. The lighting electricity and the adaptive thermal discomfort hours of 30 different models of houses were obtained using OpenStudio and EnergyPlus simulation software. The models were developed for three building shapes (square, rectangle, and L-shaped), and each model was varied in five models of window-to-wall ratios. Results indicate that the square-shaped model with a WWR of 10% will provide the lowest energy consumption in thermal comfort had 420.45 kWh/m^2. On the other side, the lowest energy consumption in lighting is the square-shaped model with a WWR of 50% had 507.95 kWh/m^2. Thus, the recommendation is to use the square-shaped house that represents the most efficient air conditioning system while the other WWR set also produce the most natural luminaire. It is because the percentage of WWR increased will result in more energy consumption in air cooling but slightly lower energy consumption in lighting. However, when considering aesthetics and freshness, the WWR of the 50% model will offer a better deal.

Keywords: Shape effects; Window and wall; Luminaire optimization; Energy optimization.

1. Introduction

The interplay between the building shape, the window-to-wall ratio (WWR), thermal comfort, and illumination in architectural design involves a nuanced consideration of various factors. Concerning thermal comfort, the size and type of windows significantly impact the indoor climate. The climate in a room is influenced by six factors, namely: the temperature, air speed, air quality, humidity, light and view [1], [2]. Larger windows offer the advantage of increased natural light penetration, fostering a bright and open atmosphere. However, this may also lead to challenges, especially in warmer climates, where excessive sunlight can elevate interior temperatures. To address this, the selection of advanced glazing solutions, such as low-E glass, becomes crucial. These technologies allow for optimal light transmission while minimizing heat gain, contributing to improved energy efficiency [3], [4].

Simultaneously, the wall area and its insulation properties play a pivotal role in regulating indoor temperatures. Well-insulated walls, constructed with climate-appropriate materials, enhance thermal resistance and contribute to a more comfortable living environment. The integration of passive design principles, such as thermal mass and proper orientation, further aids in maintaining thermal equilibrium within the living space [5].

In the realm of natural illumination, the window to wall ratio plays a vital role in determining the quality and quantity of daylight entering a room. Larger windows not only reduce the need for artificial lighting during daylight hours but also provide occupants with a connection to the outdoors, positively influencing well-being. Careful consideration of window placement and design, including the use of skylights or clerestory windows, can maximize the penetration of natural light into the interior spaces [3]. Moreover, the reflective properties of wall surfaces and the selection of wall colors contribute significantly to the overall illumination within a space. Light-colored walls and surfaces can amplify the effects of natural light by promoting light diffusion and minimizing shadows. The integration of reflective materials strategically within the architectural design can enhance the distribution of daylight throughout the interior [6].

The balanced integration of these elements requires a holistic approach that considers both thermal comfort and illumination simultaneously [7]. Collaborative efforts between architects, engineers, and environmental designers are essential to tailor designs to local climates and specific project requirements [8]–[11]. In essence, the detailed consideration of the window to wall ratio, coupled with thoughtful material selection and design strategies, contributes to the creation of energy-efficient, comfortable, and well-illuminated living spaces.

In previous work at a small office in Tripoli, Libya has been analyzed the walls with WWR between 0 and 0.9, and with orientation varied in steps of 45°. The effect of adding windows to facade results in an increase in annual total energy consumption by 6–181% [12]. Thus, this paper presents the finding of a research study, aimed to analyze the annual building energy consumption of 49 m^2 variation of house in Padang, Indonesia, the cooling load, and the lighting load with WWR between 0.1 and 0.5.

2. Material dan methods

The objects of this research are models of houses with one living room, one kitchen, one bathroom and two bedrooms. The simulation was carried out at a hypothetical location in Padang [13], which has a tropical hot humid climate. The number of family members selected was four, which is the average number of occupants per household in West Sumatra, Indonesia [14]. The selected house model is with three bedrooms, one kitchen and one living room area (five living spaces). Although most of the houses are one-story in West Sumatra, houses were chosen for the case study because more houses are built in urban areas with high energy consumption. All models are designed with flat roofs to avoid the impact of roof shading and are the current trend in urban areas.

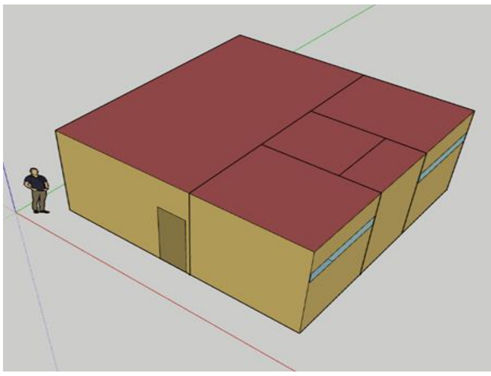
2.1 Case study

HVAC system has been the most significant component of a building system since it converted more than a half of total building energy into thermal energy. To supply thermal comfort into room throughout the year, the performance of HVAC system must be carefully measured. The lighting system are the second important part of building systems. The actual data of most shaped house is chosen from square, rectangle, and L-shaped shape located at Padang, Indonesia. For optimum solar exposure, the HVAC system and the lighting system must be positioned at a right choice corresponding to the site location [15]. Table 1 shows house specifications and parameters and Figure 1 shows models of house building shape.

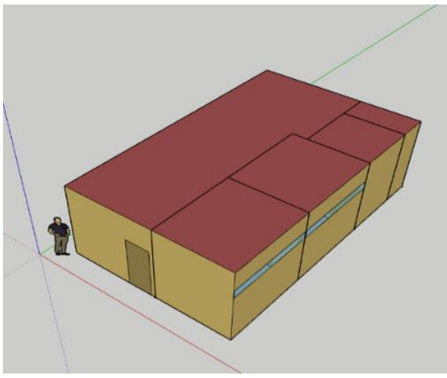
Table 1: House specification and parameters

Specification	Parameters
Building type	Residential house
HVAC system	Split AC
Luminaire system	Recessed
Number of room type	4
No. of living room	1
No. of bedroom	2
No. of kitchen	1
No. of bathroom	1
Range of total area	49 – 49.5 m^2
Square shaped area	49 m^2
Rectangle shaped area	49.5 m^2
L-shaped area	49.5 m^2
Total of doors	5
Door area	1.6 m^2

The shape of the house that will be simulated consists of three types of house buildings.



(a)



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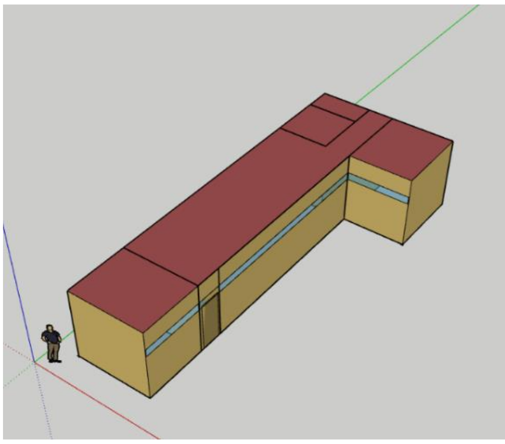

(c)

Figure 1: Models of building shape: (a) Square, (b) Rectangle, and (c) L-shaped

2.2 Hour-based schedule

The percentage of people in the room and the intensity of the activities within it can affect the amount of cooling and lighting loads. Therefore, scheduling the presence of people becomes a determining factor in energy efficiency efforts. Activity scheduling options are also included in the ASHRAE standard [16]. For residential air-cooling systems, especially during warmer months, it is essential to follow a schedule of activities to ensure optimal performance, energy efficiency, and thermal comfort. The term "hour-based schedule" generally refers to the various daily and routine activities that people engage in within their homes. These activities can vary widely based on individual lifestyles, family structures, cultural practices, and regional norms. These activities collectively contribute to the daily rhythm of life in residential spaces, shaping the lifestyle and overall well-being of individuals and families. Specific activities can vary widely based on cultural, economic, and personal factors. Several things differ between the weekday, Saturday, and Sunday schedules, but for residential homes, the schedule remains the same throughout the week. This would be easier if done manually, but Revit has compiled the data, making the convenience the same for each building schedule as presented in Figure 2.

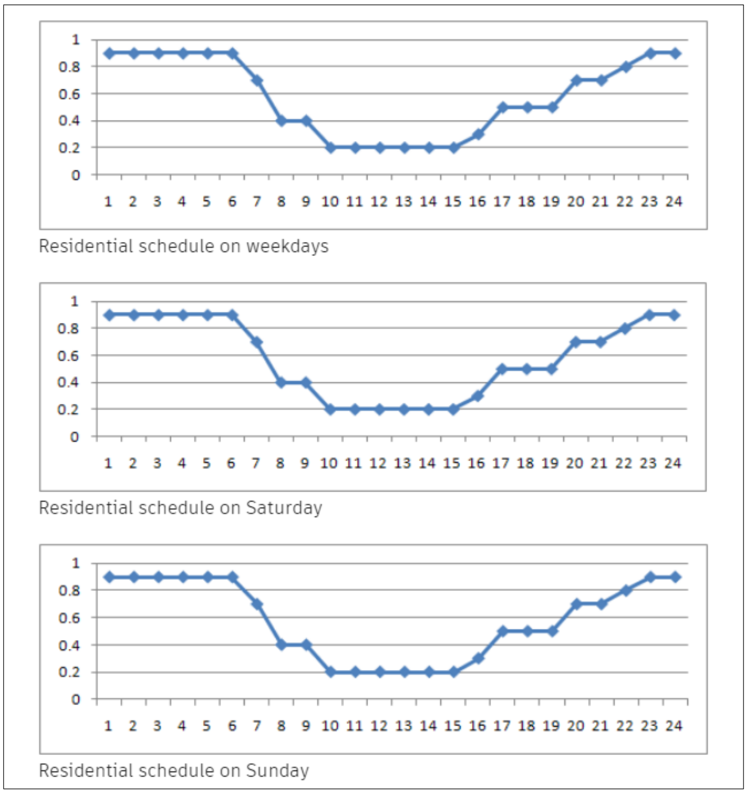

Figure 2: Residential schedule from Revit Autodesk 2020

Hour-based schedule of what people do inside a building is also a critical component of an effective air conditioning system. This component converts the percentage of energy used in the air conditioning and lighting. The total number of hours is 24 hours and the total of energy used is 100%.

2.3 Home schedule

Another thing that greatly affects the cooling load is the internal gain of people, lighting, and the infiltration of air into the room. For this building, the lighting data used is unknown so it is assumed that the building uses lighting according to ASHRAE standards. The following Table 2 is indoor standards (Space Type Data) based on ASHRAE Revit Autodesk [17].

Table 2: Home 24 hours schedule

Parameter	Value
Occupancy schedule	Home 24 hrs
Power schedule	6 am - 11 pm
People	0.1 person/m^2
People sensible heat gain	250 Btu/hr
People latent heat gain	155 Btu/hr
Lighting load density	12 W/m^2
Power load density	5.8 W/m^2
Electrical equipment radiant	0.5 %

Daily activity is one of the important parameters in air conditioning system because the size of solar radiation will affect energy consumption [18]. It is an instantaneous load density in units of W/m^2 it depends on people and equipment. Global solar radiation is the total amount of solar energy received at a particular location during a specified period often in kWh/m^2 [19]. Location of Padang city in Figure 3.

Figure 3: Location of Padang city

2.4 Luminaire application

The luminaire application refers to the various uses or installations of luminaires, which are devices that produce light. Luminaire applications encompass a wide range of lighting scenarios in both residential and commercial settings. The fraction contained in the light object is obtained from the standard indoor lamp installation [20]. The fraction value depends on the luminaire type of lighting. There are five types of luminaires are commonly used. Each type has its advantages and disadvantages for calculating building energy consumption. There are four fractions of data which can be taken into consideration including return air fraction, radiant fraction, visible fraction, and convected fraction. All the value of the fraction is used to get lighting configurations as presented in Table 3.

Table 3: Luminaire configuration

Data	Luminaire configuration, fluorescent lighting				
	Suspended	Surface mount	Recessed	Luminous and lou. ceil.	Returned-air ducted
Return air fraction	0.00	0.00	0.00	0.00	0.54
Radiant fraction	0.42	0.72	0.37	0.37	0.18
Visible fraction	0.18	0.18	0.18	0.18	0.18
Convected fraction	0.40	0.10	0.45	0.45	0.10

2.5 Variation of building shape and WWR

The next step is to carry out a simulation using the HVAC system, especially the air conditioning system commonly used in Indonesia. Therefore, a unitary HVAC system template was employed as a split AC cooling system. The variations in the shape of the house and the WWR used for simulation can be observed in Table 4, Table 5, and Table 6.

Table 4: Model of square-shaped houses configuration

No. model	Size of window (m)		No. of windows	Windows position	WWR	Windows-to-wall area (m^2)
	Height	Width				
SQ01E	1.5	0.7	2	Edge	10%	2.1/21
SQ01M	1.5	1.4	1	Middle		
SQ02E	1.5	1.4	2	Edge	20%	4.2/21
SQ02M	1.5	2.8	1	Middle		
SQ03E	1.5	2.1	2	Edge	30%	6.3/21
SQ03M	1.5	4.2	1	Middle		
SQ04E	1.5	2.8	2	Edge	40%	8.4/21
SQ04M	1.5	5.6	1	Middle		
SQ05E	2.1	2.5	2	Edge	50%	10.5/21
SQ05M	2.1	5.0	1	Middle		

Table 5: Model of rectangular-shaped houses configuration

No. model	Size of Window (m)		No. of windows	Windows position	WWR	Windows-to-wall area (m^2)
	Height	Width				
RT01E	1.5	0.7	2	Edge	10%	2.1/21
RT01M	1.5	1.4	1	Middle		
RT02E	1.5	1.4	2	Edge	20%	4.2/21
RT02M	1.5	2.8	1	Middle		
RT03E	1.5	2.1	2	Edge	30%	6.3/21
RT03M	1.5	4.2	1	Middle		
RT04E	1.5	2.8	2	Edge	40%	8.4/21
RT04M	1.5	5.6	1	Middle		
RT05E	2.1	2.5	2	Edge	50%	10.5/21
RT05M	2.1	5.0	1	Middle		

Table 6: Model of L-shaped houses configuration

No. model	Size of Window (m)		No. of windows	Windows position	WWR	Windows to wall Area (m^2)
	Height	Width				
LL01E	1.5	0.7	2	Edge	10%	2.1/21
LL01M	1.5	1.4	1	Middle		
LL02E	1.5	1.4	2	Edge	20%	4.2/21
LL02M	1.5	2.8	1	Middle		
LL03E	1.5	2.1	2	Edge	30%	6.3/21
LL03M	1.5	4.2	1	Middle		
LL04E	1.5	2.8	2	Edge	40%	8.4/21
LL04M	1.5	5.6	1	Middle		
LL05E	2.1	2.5	2	Edge	50%	10.5/21
LL05M	2.1	5.0	1	Middle		

Each table describes a different model. It compares two types of window positions: two windows at the edge or one window in the middle. The results show no difference between the two positions.

2.5 Temperature application

The desired working temperature is regulated based on SNI 03-6390-2011 standards concerning energy conservation of building air conditioning systems, namely to meet the thermal comfort of building users, a room temperature of 24 °C is used.

3. Results and discussion

The goal of this simulation is to find out how energy is used for each available cooling system so that it can be seen how the difference is and can produce recommendations according to the form and WWR with the best energy efficiency later. For this reason, an analysis of temperature comfort conditions is carried out. Effect of house shape and WWR to HVAC energy consumption is shown by Figure 4.

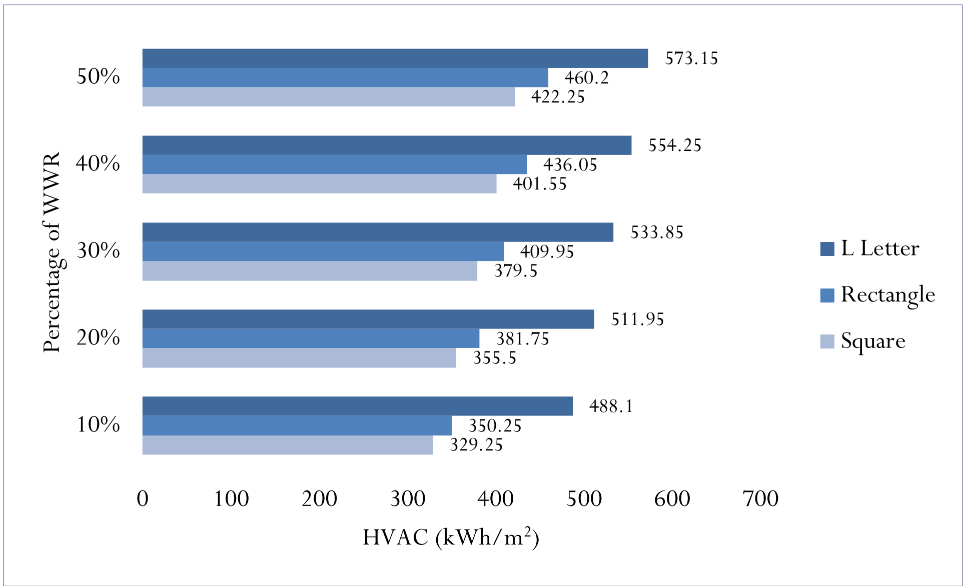

Figure 4: Effect of house shape and WWR to HVAC energy consumption

The goal of this simulation is to find out how energy is used for each available cooling system so that it can be seen how the difference is and can produce recommendations according to the form and WWR with the best energy efficiency. Effect of house shape and WWR to lighting energy consumption is shown by Figure 5.

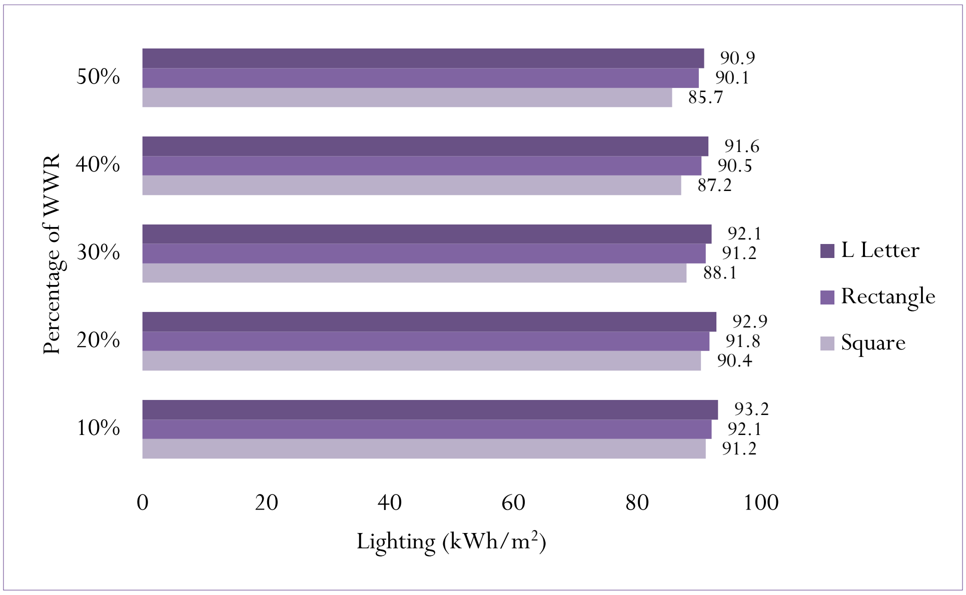

Figure 5: Effect of house shape and WWR to lighting energy consumption

In Figure 4 and 5 shows the two systems when viewed from their energy use (electrical energy) over a period of one year. The use of electrical energy is divided into several main components, namely energy for lighting and energy for air cooling. It can also be seen that the lowest energy use for air cooling is to use a square shape with a WWR of 10% while the lowest lighting is to use a square shape with a WWR of 50%. With these values, it can be concluded that the square shape is more energy-efficient for home cooling and lighting systems. The reduction in energy consumption in air cooling and lighting respectively by the addition of WWR is presented in Figure 6.

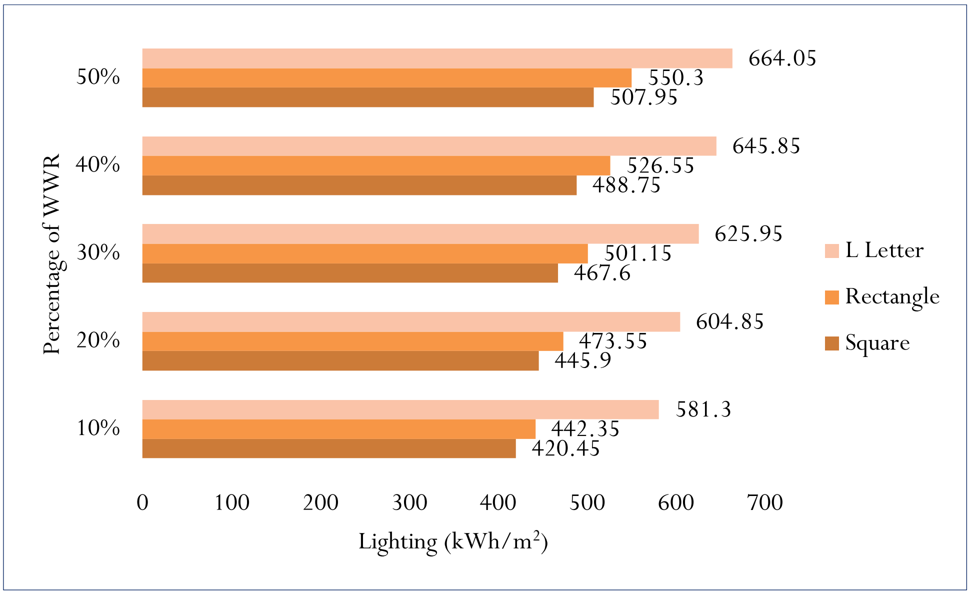

Figure 6: Effect of shape house for total energy consumption

Based on the graph in Figure 6, it can be concluded that an average of 95% of the total energy consumption comes from the use of air cooling. Based on the requirements for energy-efficient buildings according to the criteria of the Green Building Council Indonesia, this house still does not meet the requirements because if the energy is added using air conditioning and lighting systems, the total exceeds the maximum, namely 329.25 + 91.2 = 420.45 kWh/m^2. Meanwhile, the criteria from the Green Building Council Indonesia for apartment or residential buildings is 350 kWh/m^2. Table 7 shows the power amount produced by PV plant at different tilt angle.

Table 7: The power amount produced by PV plant at different tilt angle

Rank	Energy Consumption	Shape	WWR
1	420.45	Square	10%
2	442.35	Rectangle	10%
3	445.9	Square	20%
4	467.6	Square	30%
5	473.55	Rectangle	20%
6	488.75	Square	40%
7	501.15	Rectangle	30%
8	507.95	Square	50%
9	526.55	Rectangle	40%
10	550.3	Rectangle	50%
11	5813	L-shaped	10%
12	604.85	L-shaped	20%
13	625.95	L-shaped	30%
14	645.85	L-shaped	40%
15	664.05	L-shaped	50%

In the analysis of the five most optimal options, it is evident that the percentage of energy used for air conditioning is higher compared to lighting. In the most optimal option, the comparison can be obtained by referring to the innermost circle, while the fifth-ranked most optimal option can be identified from the outermost circle as presented in Figure 7.

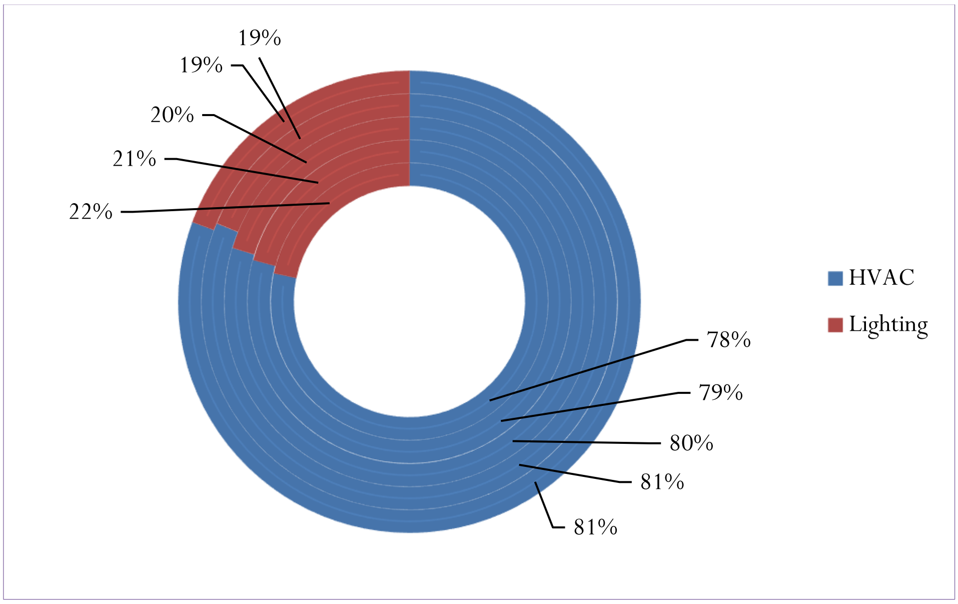

Figure 7: The top five of percentage of HVAC and lighting energy consumption

4. Conclusion

The right design building continues to play a very important role in the decreasing energy consumption. These are used inexhaustible sources of the atmosphere for the generation of power. For the simulations that are closer to reality, it is important to know certain specifications of the area, such as the geographical latitude, climatic conditions, average daily incident sunlight, tilt angle, and azimuth angle. These factors affect the overall thermal comfort in the building. The national population of Indonesia is 278.8 million (2023) with 81.08 % of the population having house which means that roughly 53 million of the population do not have house. This paper is analyzed energy consumption of the building design to increase the passive energy efficiency and at the same time reduce the energy consumption building in Indonesia. This was achieved by designing, simulation, and evaluating a square shape model with ten percent window-to-wall ratio using EnergyPlus software.

Based on the simulation results and comparing the energy consumption experienced by each model with WWR variations, the SQ01M model had the lowest total of energy consumption in air cooling and lighting. But when it compares which one the lowest energy consumption in lighting, then it had the SQ05M model. This happens because the bigger window will make the intensity of natural lighting bigger. It decreases the energy consumption in lighting but also affects the increase in thermal heat in the room (internal gain). Thus, it can be recommended to use the most efficient air conditioning system for this house because the percentage of WWR increased will make more energy consumption in air cooling but slightly lower energy consumption in lighting. However, considering the aesthetic and comfortable, the SQ05M model will offer better deals.

Author contribution

Andre Kurniawan: writing-original draft, writing-review, conceptualization, data gathering. Remon Lapisa: conceptualization, investigation, supervision. Muhammad Yasep Setiawan: gathering data, visualization. Bulkia Rahim: data analysis, visualization. Budi Syahri: writing-original draft, visualization.

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Competing interest

No potential conflict of interest was reported by the author(s).

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