Optimize electrical energy cost of air conditioning considering to different wall characteristics

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Abstract. The purpose of this study is to optimize the electrical energy cost (EC) of air conditioning (AC) with consideration of different wall characteristics. The type of wall characteristics is based on the varying composition of the wall. For example: Styrofoam, soil, calcium carbonate and iron. There are three kinds of wall that have been evaluated to design an economical building. To fulfill the goal of this research, a cooling model of building has been designed to optimize the electrical EC of the AC considering to temperature room. Under numerical optimization the electrical EC can be computed by considering thermal conductivity and outside temperature (Tout). Consequently, the electrical EC for Building-1, Building-2, and Building-3 can be reduced to IDR 25,000, IDR 23,000, and IDR 20,000, respectively.

Keywords: air conditioning; electrical; energy cost; wall.

Nomenclature:

Abbreviations

AC	Air conditioning
AM	Ante Meridiem
C_aCO_3	Calcium Carbonate
EC	Energy Cost
EMS	Energy management system
IDR	Indonesian Rupiah
kWh	Kilo Watt Hour
KSA	King Saud Arabia
Matlab	Matrix Laboratory
PCM	Phase change material
PM	Number of switches
VC	Varying composition
SISs	Switchable insulation system
UK	United Kigdom

Symbols

A	Total area (m^2)
B	Heat Transmission (W)
H	Heat Capacity of the Room (J/^{o}C)
K	Thermal conductivity (W/m.C)
L	Wall thickness (m)
P	Electricity Price (IDR/kWh)
Q	Heat Transfer Coefficient (W/m^{2o}C)
Rc	Resistance conduction (C.m^2/W)
S	Electricity power (kW)
Tin	Inside Temperature (^{o}C)
T_{out}	Outside Temperature (^{o}C)
To	Initial temperature (^{o}C)
Ts	The starting temperature (^{o}C)
T_{max}	Maximum temperature (^{o}C)
T_{min}	Minimum temperature (^{o}C)
W	Watt
X	Duration Time
Y	Binary Variable (0 or 1)
ΔT	Temperature gradient

1. INTRODUCTION

According to [1, 2] one of the main drivers of electricity demand is the rate of population expansion. Population growth is causing a rise in demand for air conditioning. One of the primary factors of rising global electricity demand is the increased use of AC. Applying AC to stay cool in residential homes already accounts for around 30%- 40% during the summer season [3]. The main concern in regard to the AC is not only for the billings paid but also the cost of providing a new power plant and the cost to the environment. Therefore, there is an urgent need for policy action to improve cooling efficiency in order to reduce cost investment, cut emission and minimize costs for consumers.

Author in [4-6] illustrates how AC usage contributes considerably to peak demand in residential buildings. In the United Kingdom, the residential electricity demand is estimated at 30 percent of the total electricity consumption and 50 percent of the national electricity peak demand [7]. In KSA, the electricity consumption due to the installed AC systems in residential homes is estimated to be more than 65% [8]. In some industrialized countries, such as Australia, Canada, France, Japan, Netherlands, Sweden, Switzerland and Spain, residential homes spent 35%-42% more electricity when consumers installed the AC [9]. In China, residential electricity consumption during summer season generates more than 40%, only for the AC demand [10]. In Egypt, the AC systems consumed 56% of the total energy output of buildings [11]. The AC issues have become particularly sensitive in both developing and advanced countries. Growing demand for AC is one of the most critical points in energy issues for some countries. Consequently, energy conservation for residential buildings must be paid more attention due to the large proportion in global energy use and potential saving for the AC in particular.

According to [12] thermal insulation is an essential factor in minimizing the energy consumption for residential building. Ref [13] investigates that wall material has a high potential effectiveness in reducing the effect of overheating a building. Author in [14, 15] explained that a wall has a major impact on lowering the electrical EC of the building. The important aspects impacting the electrical EC linked to the AC is the buildings' wall material. Ref [16] claims that wall envelope design is an advanced approach to realize cost savings potential for the AC. Consequently, selection of appropriate material for walls can be applied to minimize the electrical EC of the AC. In addition, an innovative material selection to produce a wall is required to diminish the electrical EC for the AC and keep the room comfortable.

Generally, examples of materials that have been used to manufacture a wall include wood, brick and CLC brick. Author in [17] investigates wood material selection for the manufacture of school building. Ref [18] applied PCM integrated brick material to create a wall in cooling management for residential houses. Ref [19] assessed the physical and mechanical qualities of CLC bricks due to their increased popularity in the construction market over the last decade. However, none of these materials was using an eco-composition to design the eco-wall of a building.

In addition, the electricity peak demand occurred when the user operate the AC at the same time during hot days. Refs [20-22] said the electricity use increased during hot days because of the AC. The Tout increased to a high or extreme level as consumers operated their AC at the same time. Usually, the consumer switched on the AC to a cooler level to keep rooms comfortable. Consequently, it needed more power to operate it. In contrast, when the Tout decreased to a basic level then the AC were only operated by less power. Therefore, it is required to optimize the electrical EC for the AC based on the Tout.

Previously, some studies have developed an innovative strategy to create a wall by reducing EC of building. For example: Ref [23] investigates the potential energy saving based on the cool paint modification in University of California, Davis Campus. This research analyzed building stock baseline by directly measuring solar reflection and designed a new model to compute the solar reflection from the color of the wall. As a result, an energy saving of around $45,000 can be achieved annually. Another study was developed by [24] to analyze the effect of exterior walls to conserve energy in green buildings. To achieve the aim of this research, ANSYS simulation was applied to develop a new typical and forecast the unusual condition with consideration to the thermal insulation of a wall. This simulation calculated the impact of concrete foam external walls with a thickness of 50 mm, was calculated when the concrete foam's thickness was 145 mm. The study's findings suggested that this technique is useful for preserving heat and preventing cold.

Research on minimizing the electrical EC of the AC considering the wall characteristics was developed previously in Refs. [16, 25]. Author in [16] designed a wall envelope to minimize the EC in AC buildings. The types of building materials include cinder concrete, expanded polystyrene, laterite stone, mud and burned bricks. There are 28 different composite wall combinations that can be used as insulation with various external surfaces. This study used the unstable thermal transmission data from the admittance approach to calculate the AC's potential cost reduction. Consequently, the highest annual energy saving can be achieved, such as 1.71 $/m^2 at 2 m/s. The influence of wall material on lowering the EC of the AC was shown in reference [25]. In this study, two different types of structures have been assessed: building-1, made of standard CLC brick, and building-2, made of an inventive CLC brick. A mathematical model has been created to calculate the best solution in order to determine the EC. As a result, building-2's EC for the AC was less expensive than building-1's.

However, even though some methods were examined, none of these studies specifically developed an innovative material to create a wall which can be applied to reduce the electrical EC for AC, considering thermal conductivity and Tout.

To bridge the research gap, this paper's goal was to create an economic-building to decrease the EC of the AC considering different wall characteristics. There are two major contributions discussed in this paper. Firstly, compute Tin and EC of the AC considering the thermal conductivity. Secondly, compute Tin and EC of the AC considering the thermal conductivity and Tout.

2. METHODS

2.1 An explanation of the issue

Residential electrical energy use has been rising rapidly as a result of the AC load. The majority of energy used in residential home is for maintenance and comfort. Walls have a big effect on keeping a space comfortable and can reduce bills of electricity over time by saving energy for the AC. To construct a new model of wall, some techniques have been used. But none of the earlier research used a novel material to create a building wall. The types of materials are composed of: Styrofoam, soil, C_aCO_3 and iron. This research, optimizing the electrical energy costs of the AC, considering three kinds of different wall characteristics.

2.2 Varying composition of wall

To optimize the electrical energy cost of building, there were three kinds of different wall characteristics considered. These were based on the varying compositions to create a wall. Table I (below) illustrates the varying composition for each different wall.

Table I. Varying composition

Wall	Varying composition			
	Styrofoam (%)	Soil (%)	CaCo3 (%)	Iron (%)
1	5	94	0.5	0.5
2	10	88.8	0.6	0.6
3	15	83.6	0.7	0.7

Table I illustrated the kind of materials required to make an inventive CLC brick. Only 5% of Styrofoam, 94% of soil, 5% of iron, and 5% of C_aCO_3 are used in the VC-1. On the other hand, the percentages of Styrofoam, soil, C_aCO_3, and iron in the materials used to make an inventive CLC brick of VC-3 were: 15%, 83.6 percent, 0.7 percent, and 0.7 percent, respectively.

2.3 Wall design and building model

Figures 1 and 2 below show a wall design and a building model, respectively. The inventive CLC brick produced a wall design. A model of a single room that might represent an entire apartment building was created. The size of this single room model is 5 meters long, 5 meters wide, and 3.5 meters high. In the modelling phase, the entire building envelope is simulated and connected to the AC and ventilation system. To make things easier, the heat transfer interaction between the interior and exterior temperatures caused by convection and radiation was not taken into account when calculating the room temperature inside the enclosure. In this study, the heat transfer was conducted only to consider the conduction process.

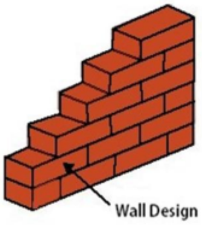

Figure 1. Wall design

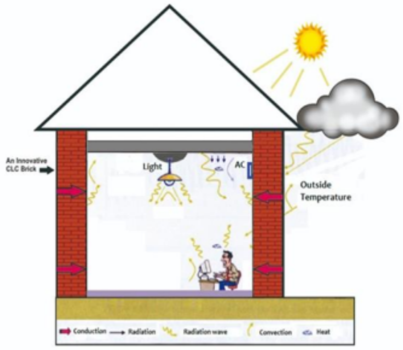

Figure 2. Model of building

2.4 Heat transfer and cooling model of building

In this study, a composite wall comprises a number of layers with different properties (see Figure 3). The kind of wall characteristics are according to the amount of its material composition. Consequently, a number series or parallel thermal resistance arises due to the different layers of materials. The heat transfer rate is associated with difference in temperature and thermal resistance can be computed by the following equation [26].

$$Q = \frac{\Delta T}{\sum R_c} \tag{1}$$

$$R_c = \frac{L}{K.A} \tag{2}$$

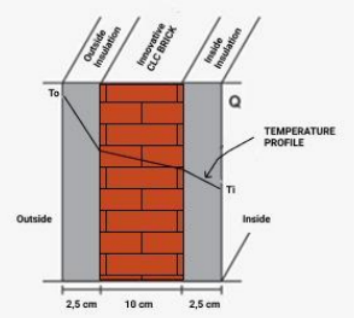

Figure 3. The composition of a wall

In addition, the temperature distribution of the wall can be calculated based on the following equation[27]:

$$T_{(x,y)} = \frac{4\,T_1}{\pi}\sum_{1}^{\infty}\frac{\sin[(2n-1)\frac{\pi x}{X_1}]}{(2n-1)}\frac{\sinh[(2n-1)\frac{\pi y}{X_1}]}{\sinh[(2n-1)\frac{\pi Y_1}{X_1}]} \quad (3)$$

To manage the Tin and determine the EC of the building's AC, a cooling model for the building has been established. The control system manages the Tin for the user and finds a lowest EC. Under numerical optimization, the effect of Tout and thermal conductivity of building to Tin and EC have been evaluated. Consequently, the Tin can be comfortable for the consumer and the minimum EC can be achieved. In addition, Matlab simulation is applied to define the Tin, EC and displays the result in the same plot. Figure 4 (below) indicates the kind of cooling model of the building.

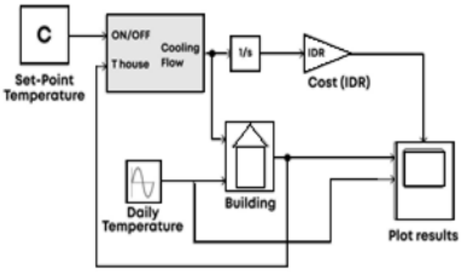

Figure 4. Cooling Model of building

2.5 Electrical energy consumption

The following equations (4) and (5) illustrate the minimum energy consumption of a residential building:

$$EC(t) = \int_{t=1}^{t=n} [(S(t).P(t).X(t).Y(t))\ dt] \quad (4)$$

Subject to constraints:

$$\frac{dT}{dt} = \frac{Q.\ A.\ (T_O(t) - Tin(t))}{H} - \frac{B.Y(t)}{H} \quad (5)$$

To compute the minimum EC, the AC was turned on and turned off according to Tin. The AC was turned ON when the AC reached the permitted maximum temperature. In contrast, the AC was turned OFF if the AC dropped to the maximum permitted temperature. In this study, outside room temperature and characteristics of building were considered to calculate the minimum EC. Figure 5 shows the temperature on hot days in Barru, South Sulawesi, where the Tout was used to support this model (below).

Figure 5 shows an illustration of tout in Barru, South Sulawesi, during the entire day of July 17, 2021.. Figure 4 indicates that the lowest Tout basically conducted before 11:00 in the morning and after 16:00 in the afternoon. The Tout increased to a high level, namely 32°C starting from 10:30 to 16:00 in the middle of the day. Moreover, the extreme Tout was computed between 12:00 and 14:00 in the middle of the day, above 34°C. In this study, the hot days are recognized when the Tout is more than 32°C. Therefore, the hot days were identified from 11:00 to 16:00 when the Tout ≥33°C.

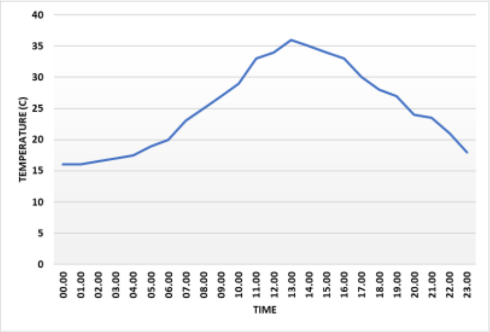

Figure 5. Outside Temperature data of July 17th 2021

3. NUMERICAL RESULT

3.1 Temperature Distribution of the wall

Figures 6-8 below illustrates the temperature distribution of the wall. Due to the different varying compositions, the temperature distribution for every type was not similar. These Figures below illustrated the plot of temperature distribution due to the conduction process of the wall. The length and width of the wall is divided into 10 and 15 segments. The point temperature for every segment is defined by adding k terms from the Fourier series. The heat transfer occurs through this material by conduction from outside to inside temperature. The temperature distribution in this material can be determined by equation (3).

Figures 6-8 above illustrates that due to the characteristic material of every kind of wall then the distribution temperature was not similar. The different result of temperature distribution at each point is due to the effect of Styrofoam composition in particular, as Styrofoam has a high thermal resistance. Combined with other materials such as soil, $\mathrm{C_aCO_3}$ and iron, the temperature distribution of the walls was not identical for every type. Consequently, the temperature distribution at each point for type-3 was slowly increased in comparison to other types. In contrast, due to the quantity of Styrofoam composition then the temperature distribution for type-1 increased more quickly than other types.

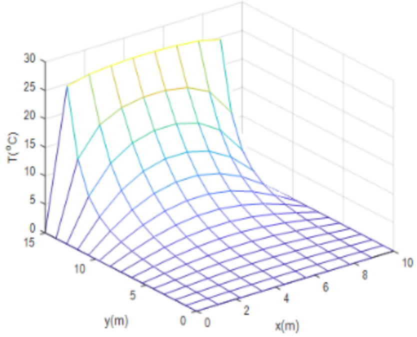

Figure 6. The Q of wall (type-1)

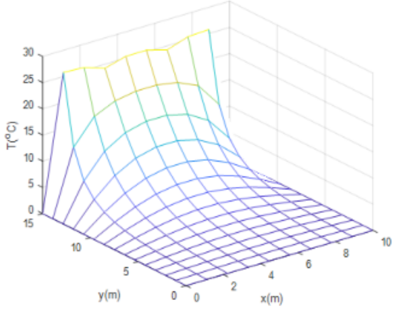

Figure 7. The Q of wall (type-2)

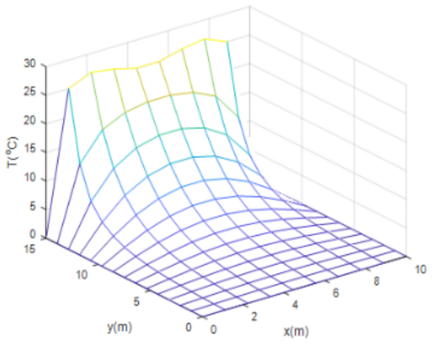

Figure 8. The Q of wall (type-3)

3.2 Case 1: Tin and EC of building considering thermal conductivity

Equation (4) and (5) were applied to define Tin and EC of the AC. Figures 9-11 illustrates the result of optimization Tin and EC of the AC for every kind of building. The inside room temperature was defined based on the thermal conductivity. To optimize the EC and maintain comfort for Tin, the minimum and maximum permitted temperatures were 21.2°C and 25°C. When the Tin's temperature reached the upper limit allowed, the control system turned on the AC. On the other hand, the AC switched off once the Tin dropped to the minimum permitted temperature. This continued until the time to operate the AC had expired.

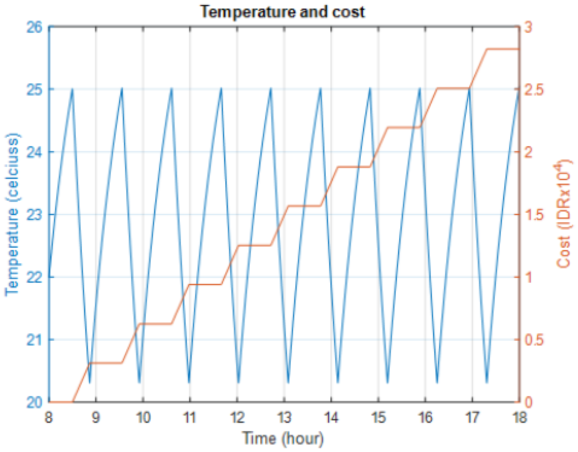

Figure 9. Result of Optimization building-1

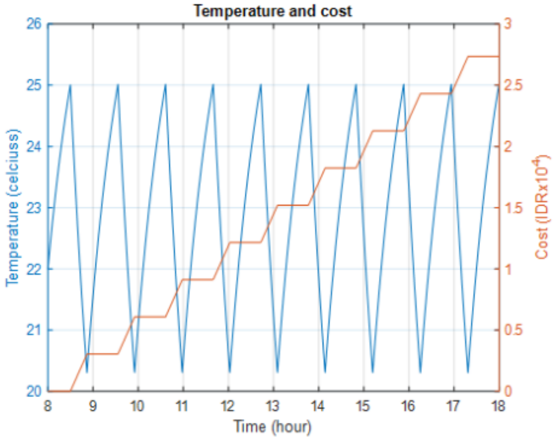

Figure 10. Result of Optimization building-2

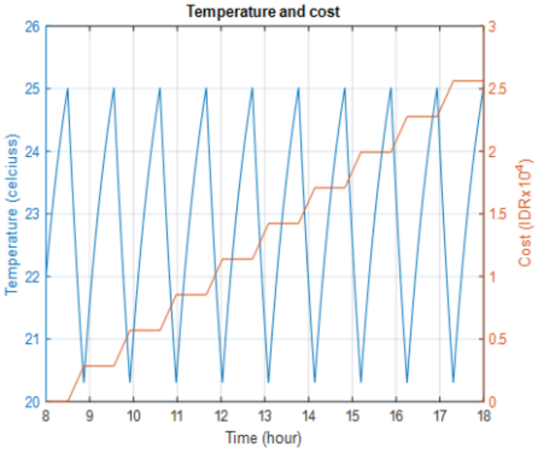

Figure 11. Result of Optimization building-3

The result of optimization indicates that the Tin and the EC of the AC for every kind of building were not similar. The thermal resistance for every building was not identical Due to the wall's construction in materials. The thermal resistance of building-1 was lower than other buildings. To run the AC, the control system requires additional electricity power. In contrast, thermal resistance of building-3 was higher than other buildings. The control system needs less power to operate the AC. Consequently, the EC can be minimized to be IDR 28,000; IDR 27,500 and IDR 26,000 for building-1, building-2 and building-3, respectively.

3.3 Case 2: Tin and EC of building considering to thermal conductivity and Tout

Equation (4) and (5) are used to compute the Tin and EC of the building considering the thermal conductivity and Tout. In this study, the Tmin and Tmax permitted temperatures were 21.2ºC and 25ºC. The time to operate the AC operated from 08:00 to 18:00. Comparable to the earlier approach, the AC was turned on if the Tin reached the Tmax permitted temperature and switched off when the Tin dropped to Tmin permitted temperature. However, to optimize the EC and keep the room comfortable, considering thermal conductivity and Tout then the pattern of Tin for every kind of building is different. Due to the Tout being increased in the middle of the day then the Tin dropped to a low level, under 24ºC. The cycling temperature range during hot days is 21.2ºC to 23.8ºC, as illustrated in Figures 12-14.

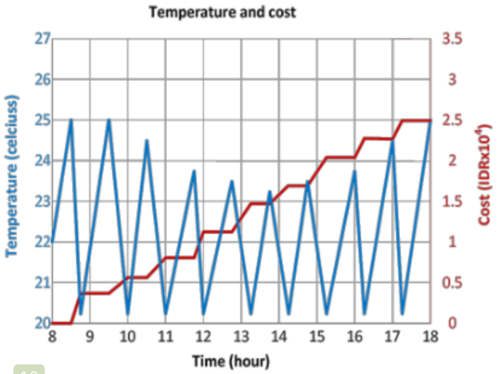

Figure 12. Result of Optimization building-1

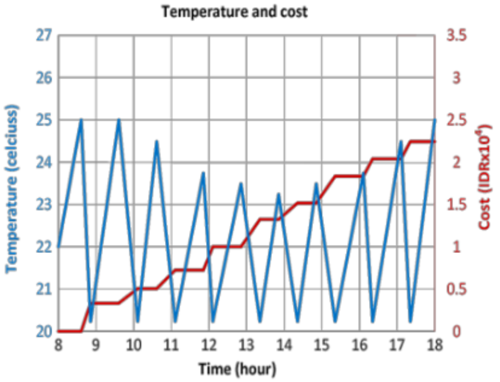

Figure 13. Result of Optimization building-2

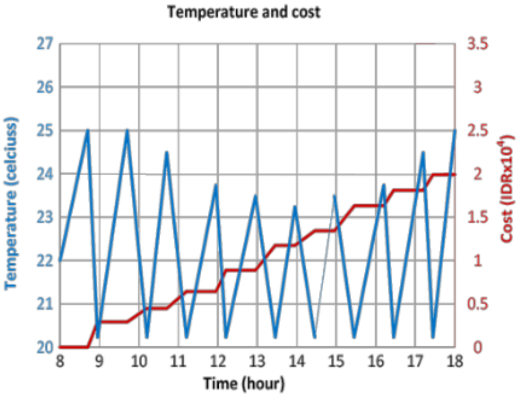

Figure 14. Result of Optimization building-3

Based on the result of optimization, the Tin decreased to low level starting from 11:00 until 16:00. Due to the different wall characteristics, the times to switch the AC on and off were not the same for every type of building. For example, the AC was switched on at 11:00 and switched off at 11:40 for building-1. The AC was turned on at 11.05 and switched off at 11:50 for building-2, while the AC switched on at 11:15 and switched off at 11:58 for building-3. In addition, the form of the cycling temperature is not only based on the thermal conductivity but also depends on the fluctuation of Tout. The control mechanism turned on the AC to decrease the Tin when the Tout was raised to a high level. In contrast, as the Tout dropped to a lower level, the Tin rose to the highest temperature allowed. Therefore, the EC can be decreased to be IDR 25,000; IDR 23,000 and IDR 20,000 for every building-1, building-2 and building-3, respectively.

3.4 The Electrical Energy Cost of Building

Figure 8 (below) illustrates the EC of the AC considering thermal conductivity.

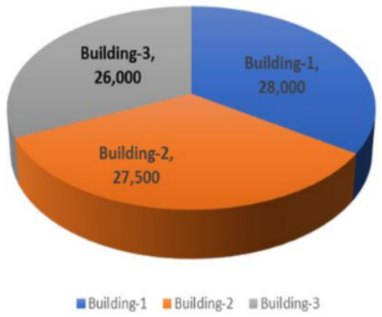

Figure 15. The Electrical energy cost considering thermal conductivity

The optimization result indicated that the EC for the AC for every building was variable. The EC of building-1, building-2 and building-3 were IDR 28,000, IDR 27,500 and IDR 26,000. The EC of building-1 was more expensive than other buildings because the thermal wall resistance of building-1 was lower than building-2 and building-3. The amount of Styrofoam as a bonding material was only 5% for building-1. In contrast, the amounts of Styrofoam for building-2 and building-3 were 10% and 15%, respectively. This specifies that the material of Styrofoam to create a building wall has noteworthy impact in minimizing the EC of the AC.

Figures 9 (below) illustrates the EC of the AC considering both Tout and thermal conductivity.

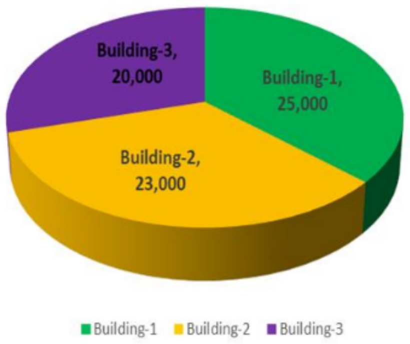

Figure 16. The Electrical energy cost considering both Tout and thermal conductivity

As illustrated in Figure 9 the EC of the AC for building-1, building-2 and building-3 were IDR 25,000; IDR 23,000 and 20,000. The thermal resistance of building-3 was higher, the EC of the AC was inexpensive than building-1 and building-2. This is due to the building's material mix, which included using more Styrofoam than the other structures. The Styrofoam has a high thermal resistance to maintain inside room temperature and to obstruct heat transfer speed from external to interior walls. In addition, Tout has a direct substantial effect in computing the EC of the AC for every kind of building. According to Tout, The Tin was controlled by the system to turned on and off. The time to switch it on during hot days was only brief. As a result, the AC only requires less power to keep the room comfortable.

4. CONCLUSION

The optimization of electrical EC for the AC for various wall features is discussed in this study. The findings of the optimization showed that the wall and Tout's material composition directly affects EC of the AC minimization. The type of material composition, including how much Styrofoam is used to build a wall, is important because Styrofoam has a high thermal resistance that prevents heat from transferring from outside to interior walls and maintains a comfortable temperature in the room. In addition, in this optimization process, the control system only needs a brief period to switch on the AC during hot days. Therefore, the EC can be minimized to IDR 25,000, IDR 23,000, and IDR 20,000 for Buildings 1, 2, and 3, respectively.

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DECLARATION OF COMPETING INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

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