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Semi-Transparent PV and Double-Glazed Windows for Heat Reduction and Electricity Generation: A Study for Office Buildings in Tropical Climate

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ABSTRACT

This research aims to develop a methodology for the evaluation of the potential energy saving and energy generation of semi-transparent PV and double-glazed window in Indonesia office buildings. The evaluation is based on Comsol software. The heat transfer equations for the inside the enclosure between the glass have been constructed according to the natural convection equation. The simulations were accomplished for four orientations from January until December and compared to a single-glazed window. The results show that it is possible to reduce the energy consumption for artificial lighting and air-conditioning using appropriate control systems and furthermore to generate electricity using semi-transparent photovoltaic panels in windows. The use of semi-transparent PV and double-glazed window has proven to be more effective in reducing heat transfer in buildings and generate electricity. East-facing double-glazed windows produce the most electricity, approximately 341 kWh.

Keywords: Heat transfer; Double-glazed window; Comsol; Photovoltaic; Thermal system

INTRODUCTION

One aspect of the building that is frequently exposed to sunlight is the window. Window made of glass enable sunlight to infiltrate the room, inducing it to become warm or hot. The thermal performance of the window has a significant impact on energy consumption in a building, whether for cooling or heating purposes. Thermal comfort is influenced by a building's thermal performance (Ismail & Rashid 2023). Thermal comfort in buildings is closely linked to energy consumption. (Wang et al. 2017). Installing double-glazed windows is one method of reducing energy loss through windows. Korpela et al. (1982) was the first to investigate the problem of heat transfer via double-glazed windows. He restricted his research to aspect ratios less than 20, which Lee and Korpela (1983) expanded to aspect ratios up to 40 with different working fluids. Novak and Nowak (1993) explored several boundary layers for enclosures with aspect ratios ranging from 10 to 20 and varying heating intensities.

Muneer and Han (1996) investigated heat and mass transfer across an enclosure. It was discovered that the usage of gases such as krypton and xenon resulted in significant energy savings. The energy analysis of the four main types of materials used to manufacture double glazed windows was then summarized by Weir and Muneer (1998). To fill the enclosure, four materials are used: wood, aluminum, glass, and gas. They analyzed the energy consumption and environmental impact of the window manufacturing process. Aydin (2000) examines the use of double-glazed windows in four different cities: Antalya, Trabzon, Ankara, and Kars, as well as how to calculate the proper thickness between the window panes. The ideal thickness between the glass, according to him, is highly influenced by the climate. Then, Aydin (2006) enhanced his research by considering the effect of the enclosure's thermal conductivity to gas conductivity ratio. It was discovered that employing a gas with a lower conductivity value can lower the insulating value.

Sun energy is the cheaper and cleaner reserve supply for all human beings. The energy from sunlight intercepted by the earth is about 1.8×10^{11} MW, which is several times greater than the total amount of global energy consumption (Parida et al. 2011). Photovoltaic (PV) technology is one of the smartest ways to collect solar energy. When windows are combined with PV, they get the ability to generate electricity and the regular functions. Previously, Sylvester and Haberl (2000) used this approach to conduct an energy simulation for high-rise buildings in four cities in the United States. The influence of the thickness of the air gap in the cavity on heat transmission through the glazed enclosure was evaluated by Han et al (2009). Didone (2013) suggested that the potential of this technology is high in Brazil. Othman et al. (2014) analyzed thermal performance of double-glazed window with semi-transparent PV. The results showed that the PV window greatly reduced the building's electricity use. Mustapha et al. (2018) analyzed the energy and exergy efficiency of a PVT collector with different designs and types of working fluids. Cheng et al. (2019) used parametric analysis to determine the yearly daylighting quality of the double pane window and net power usage for a general reference office in China's cold area. However, the thermal transmittance or U-value of the glazed was not explored in his research. Recently, Jelita and Saleh (2023) considered the conjugate heat transfer across PV.

It is essential to investigate the best design for evaluating semi-transparent PV and double-glazed windows because the U-value, thermal performance, and electricity generation from photovoltaics are linked. A computer simulation was used in this study to evaluate the applicability of windows integrated with semi-transparent PV to office buildings in Indonesia. The study's goals were to determine the U-value and thermal performance and to evaluate potential electricity generation in office buildings for four orientations from January until December and compare them to a single-glazed window.

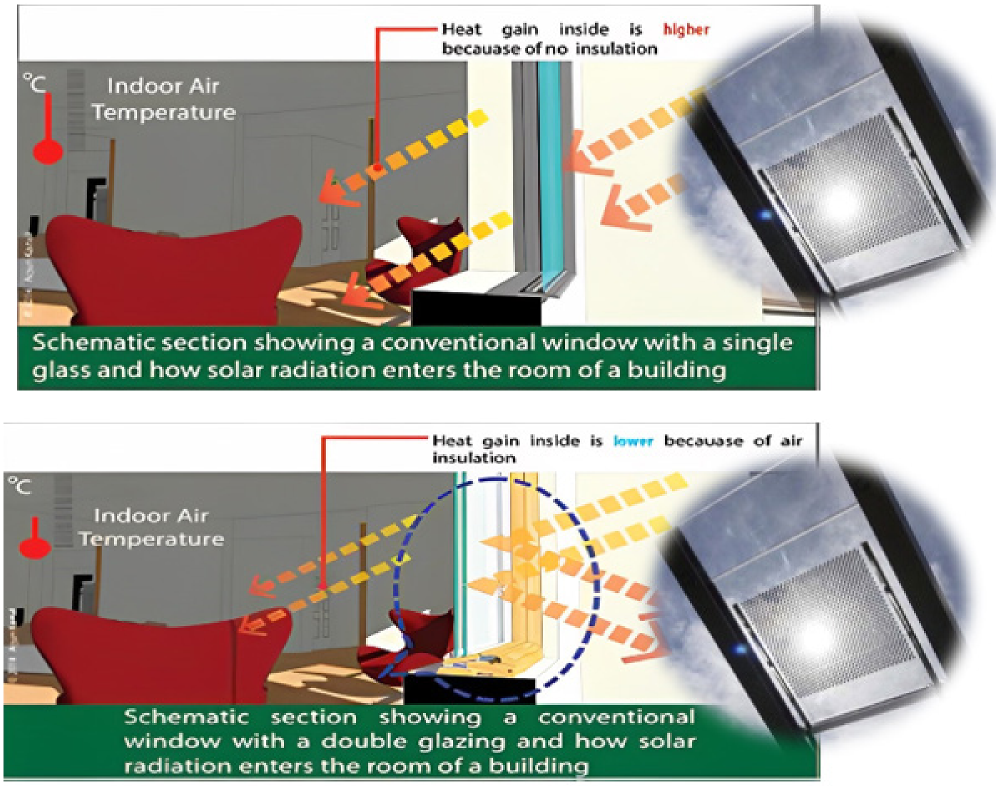


FIGURE 1. Schematic model of single-glazed window (top) and semi-transparent PV and double-glazed window (bottom)

MATHEMATICAL FORMULATION

An office building in Pekanbaru, Indonesia, was used to run the computer simulation. Schematic semi-transparent PV and double-glazed windows in this research were modeled in Fig. 1. Double glazing window, is a type of window that consists of two glass panes separated by a layer of air. Fig. 1 depicts semi-transparent PV and double-glazed windows, as well as how sunlight enters a building's room. The gap between the glasses is filled with air. Because of the air insulation, heat gain inside the room is reduced. A schematic section of a conventional window with single glass is also included at the top of Fig. 1. It illustrates a single-glazed window and how sunlight penetrates a building's room. Because there is no insulation, heat gain within the room is higher.

The study assumed an amorphous silicon solar cell type PV window due to its aesthetic advantage for use in windows. The basic structure of the solar cell is identical to that of conventional amorphous silicon solar cells. However, the solar cell's small pores make it semi-transparent. Natural light transmission is one of the benefits of the semi-clear solar cell since the spectrum of the transmitted light is nearly identical to that of the incident light. By adjusting the size of the holes, the transmittance of the semi-clear solar cell may be adjusted.

The PV panel as sketched in Fig. 1 is subject to energy from the sunlight, converts some of the irradiances into electricity via the photovoltaic effect and the remaining irradiance becomes heat. The irradiance exposes the whole PV. The PV surface has a constant and uniform temperature variation

TABLE 1. Thermo-physical properties of glass and PV

Properties	Glass	PV
Cp (J/kg K)	750	700
ρ (kg/m^3)	2180	2285
k (W/ m K)	1.38	0.25
d (mm)	3	3
L (cm)	80	80
P_{max} (Wp)	-	127

When the sun's heat shines on PV and there is solar energy that cannot be utilized properly in the form of heat on the surface of the panel, then the heat conduction through the PV cell and glass can be stated as:

$$\nabla.(k\nabla T) = 0 \tag{1}$$

Inside the enclosure occurs by convection and conduction. The convective flow is considered to be steady, incompressible, Newtonian and laminar. The density difference with the temperature in the gravitational force term is assumed to be linear based on Boussinesq's model. The model is accurate when density variations are small enough no impact on the convective flow, except that they give rise to gravitational forces, based on this consideration the continuity, momentum, energy stated as:

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \tag{2}$$

$$\begin{gathered} U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = \\ -\frac{1}{\rho}\frac{\partial P}{\partial X} + \frac{\mu}{\rho}\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) \\ U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{1}{\rho}\frac{\partial P}{\partial Y} + \frac{\mu}{\rho} \end{gathered} \tag{3}$$

$$\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) + \beta g(T - T_{ref}) \tag{4}$$

$$U\frac{\partial T}{\partial X} + V\frac{\partial T}{\partial Y} = \alpha\left(\frac{\partial^2 T}{\partial X^2} + \frac{\partial^2 T}{\partial Y^2}\right) \tag{5}$$

Here (U, V) are velocities vector, T is temperature and P is pressure. Symbol g is the acceleration due to gravity, μ, ρ, β and α are dynamic viscosity, the density, thermal expansion and thermal diffusivity of the air at atmosphere temperature, respectively.

The PV cell efficiency is calculated using formula:

$$\eta_{pv} = \eta_{ref}\left[1 - \beta_{ref}\left(T_{pv} - T_{ref}\right)\right] \tag{6}$$

Losses from a PV cell is calculated using formula:

$$L_{pv} = \eta_{pv}/\eta_{ref} \tag{7}$$

The electrical output was formulated as a function of the losses from PV cell, the PV cell surface area and solar irradiance. The received electrical energy by PV module exposed to solar irradiance is defined as:

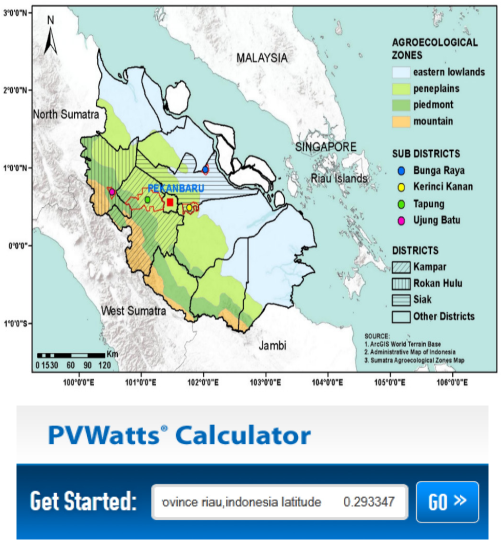
$$P_{pv} = P_{max}\, L_{pv}\, q_{rad} \tag{8}$$

The thermal transmittance or U value is evaluated as:

$$U = 1/R_t \tag{9}$$

Where R_t is total thermal resistance from all layers.

The strength of solar irradiation varies depending on location and time of year, since it is affected by factors such as latitude, longitude, altitude, and atmospheric conditions. In general, the monthly average intensity of solar irradiation is greatest towards the tropics and declines as one moves towards the arctic. We utilize the PV Watts Calculator to obtain an efficient prediction of solar irradiation in Riau Province. By inputting the location as shown in Figure 2, we can get an accurate prediction of the solar irradiation from January to December for all orientation.



ovince riau,indonesia latitude 0.293347

FIGURE 2. PV Watts Calculator to obtain the solar irradiation data in Riau Province

Figure 3 plots solar irradiation intensity each month in Riau Province, Indonesia. The west and south orientations have the same radiation statistics, with the highest radiation occurring in January at 114 W/m^2 and the lowest in September at 62 W/m^2, while the eastern orientation has the highest radiation in June at 114 W/m^2 and the lowest in March and December, both at 63 W/m^2. The highest north orientation was 104 W/m^2 in June, while the lowest was 65 W/m^2 in December. PV cells oriented straight south receive the most direct sunlight and have the highest solar irradiation intensity.

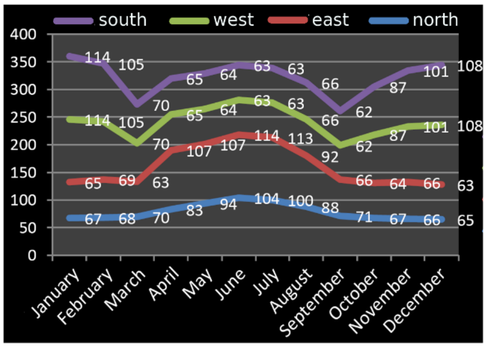


FIGURE 3. Solar irradiation intensity each month in Riau Province, Indonesia

COMPUTATIONAL METHODOLOGY

Figure shows the geometric model drawn on a diagram of the actual semi-transparent PV with double-glazed window (top of Figure 4). The geometry contains six rectangles as plotted in the bottom Figure 4 following actual dimension of the window.

The continuity, momentum and energy equations are solved numerically by using the Finite Element Method (FEM) via Comsol. The principle of FEM is dividing the domain into sub-domains. We consider the following application modes in Comsol. The heat transfer in solid (ht) for equation (1). The incompressible flow, laminar flow (spf) are used for equations (2)–(4), see Figure 5(a). The heat transfer in fluids (ht) is used for Eq. (5) as shown in Figure 5(b). Figure 5(c) is inputting radiation strength from data inside Figure 3.

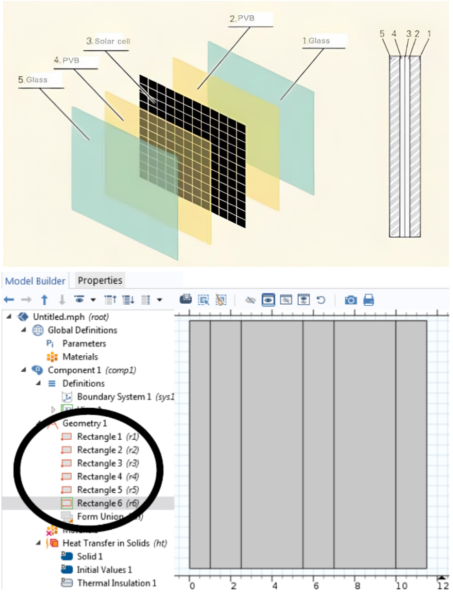


FIGURE 4. Building geometry model in Comsol

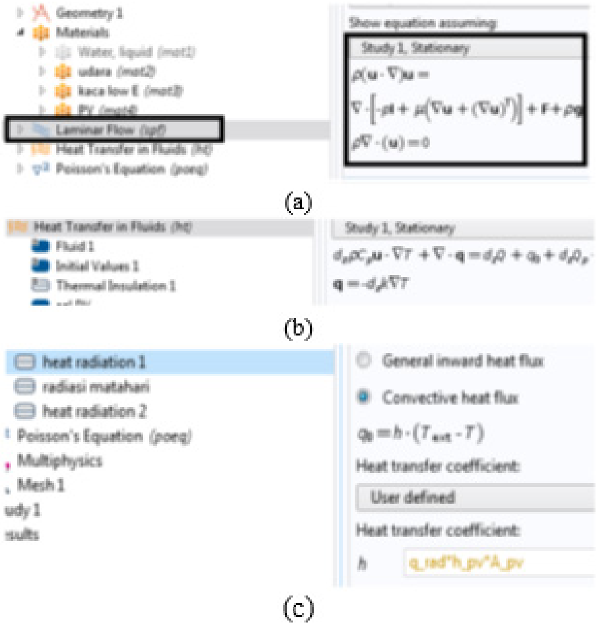


FIGURE 5. Building equation model in Comsol

RESULT AND DISCUSSION

Parametric studies are applied to analyze the PV cell efficiency, electrical energy output, thermal efficiency and rate of thermal energy by varying the orientations and the data were used during a twelve-month period from January to December.

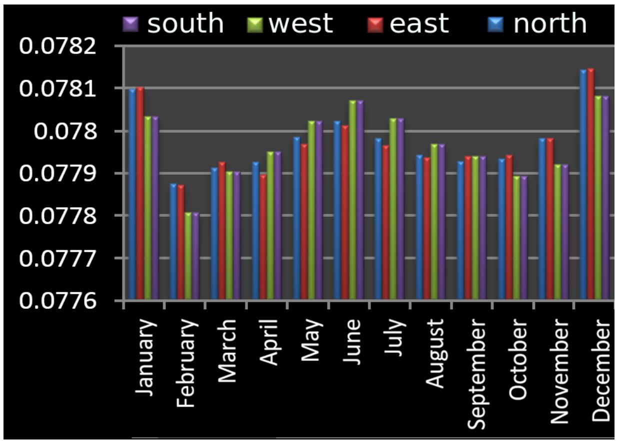


FIGURE 6. PV cell efficiency during a twelve-month period from January to December at various orientations

PV cell efficiency during a twelve-month period from January to December at various orientations is shown in Figure 6. It depicts the highest efficiency of PV cells for each orientation in December, namely a west orientation of 0.078081, an east orientation of 0.078146, a north orientation of 0.078143, and a south orientation of 0.078081. In February, the effectiveness of PV cells for each orientation is at its lowest, with a west orientation of 0.077807, an east orientation of 0.077872, a north orientation of 0.077875, and a south orientation of 0.077807. Where it can be observed that there is no substantial drop in efficiency because the solar radiation values for each orientation are not excessively high. Because the higher the solar radiation, the lower the efficiency of the PV cell; conversely, the lower the radiation produced, the better the efficiency.

Figure 7 displays electrical energy output during a twelve-month period from January to December at various orientations. The plot shows that the eastern orientation generates a significant amount of electrical energy in June (341.1195819 kWh) and July (339.6651589 kWh). However, the eastern orientation loses energy in March (189.1628869 kWh) and December (189.6967745 kWh). The west and south orientations generate enough electrical energy in January (342.4659229 kWh) and December (325.2163803 kWh). However, the electrical energy consumed by the south and west orientations dropped by 185.4355092 kWh in September. In June, the north orientation produces the most electrical energy, 311.0607952 kWh. This month has the highest levels of radiation intensity, resulting in the greatest amount of electricity generated. In December, there was a reduction in electrical energy of 195.9705961 kWh.

Figure 8 shows the U value during a twelve-month period from January to December at various orientations. As shown in Figure 8, the U value has increased for each orientation in March and September, with the north orientation reaching 6.142 W/m^{2}K in March, the east orientation reaching 5.730 W/m^{2}K in September, and the west and south orientations experiencing an increase in the U value of 6.142 W/m^{2}K. In September, the U value increased, with the northern orientation experiencing a significant increase in U value of 6.199 W/m^{2}K, the eastern orientation experiencing a significant increase in U value of 5.910 W/m^{2}K, and the west and south orientation experiencing a significant increase in U value of 5.668 W/m^{2}K. Because of the significant amount of heat streaming into the room, a high U value will increase electricity consumption.

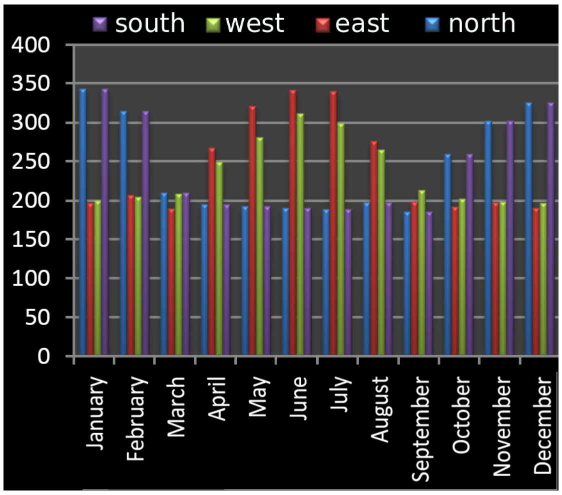


FIGURE7. Electrical energy output during a twelve-month period from January to December at various orientations

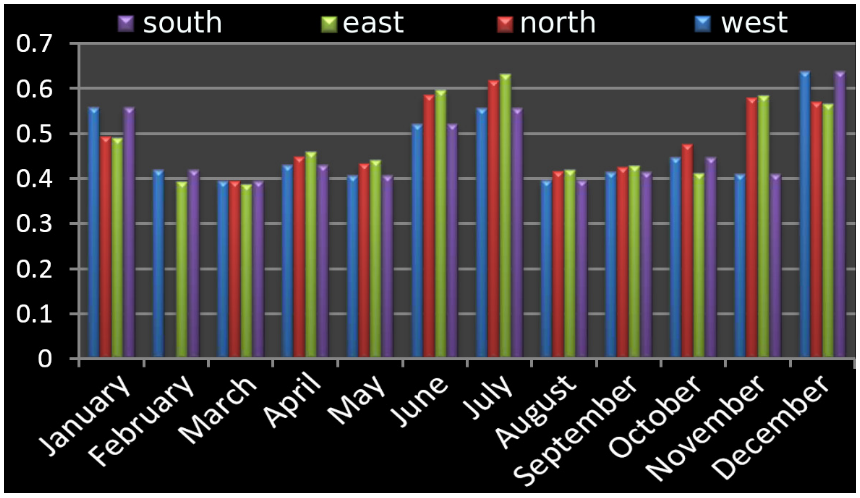


FIGURE 8. The U value (W/m^{2}K) double-glazed during a twelve-month period from January to December at various orientations

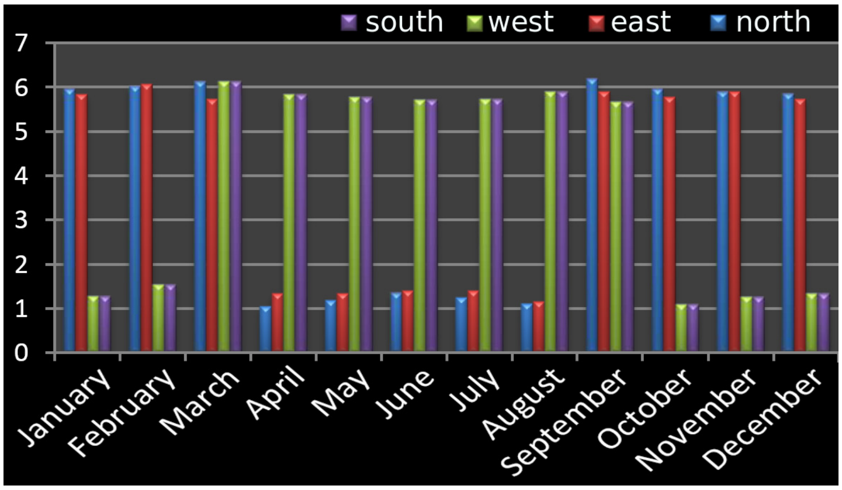


FIGURE 9. The U value (W/m^{2}K) single-glazed during a twelve-month period from January to December at various orientation

Figure 9 shows that the U value increase in all orientations in March and September, with the north orientation reaching 6.142 W/m^{2}K, the east orientation reaching 5.730 W/m^{2}K, and the west and south orientations experiencing an increase in U value of 6.142 W/m^{2}K. The U value on single-glazed increased in September, with the northern orientation experiencing a very considerable rise, namely 6.199 W/m^{2}K, the east orientation being 5.910 W/m^{2}K, and the west and south orientations being 5.668 W/m^{2}K. Because of the significant amount of heat streaming into the room, a high U value will increase electricity consumption.

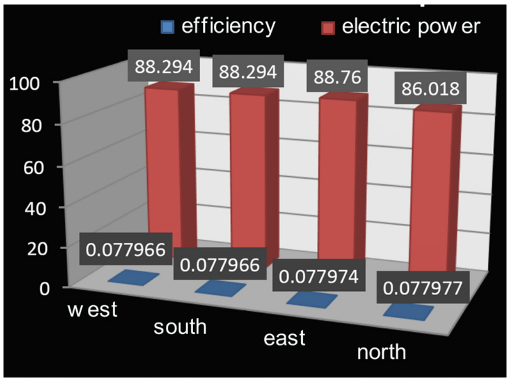
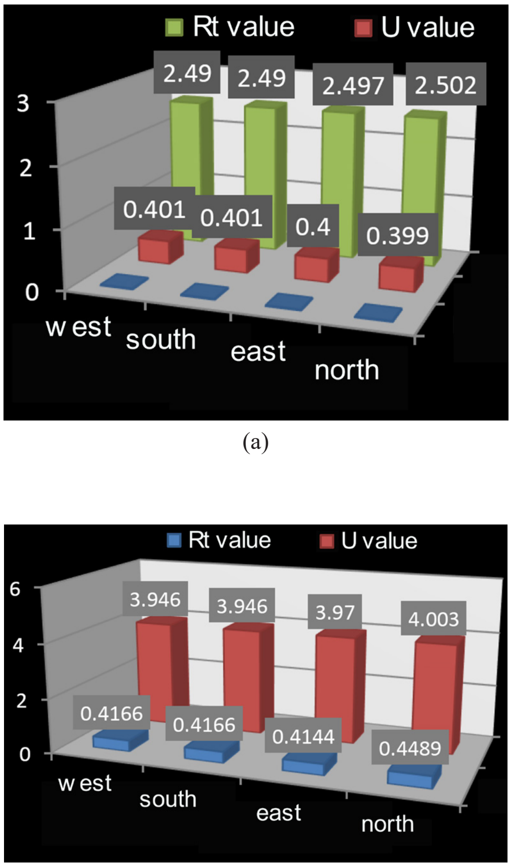


FIGURE 10. Cumulative electrical energy output from PV and cell efficiency against various orientation

Figure 10 shows cumulative electrical energy output in one year from PV and cell efficiency against various orientations. Semi-transparent PV integrated double-glazed windows are more energy efficient than single-glazed windows, which cannot generate electrical energy. The amount of electricity produced in one year is 88.760 MWh for an east orientation with an average PV cell efficiency of 0.077974, 88.294 MWh for a west and south orientation with a PV cell efficiency of 0.077966, and 86.018 MWh for a north orientation with a PV cell efficiency of 0.077977. PV cells facing north gather a steady quantity of radiation throughout the day. North-facing cells are the best option in Riau Province because the sun stays fairly low in the sky in the daytime.

Figure 11 shows the thermal resistance and U value of double-glazed (a) and single-glazed (b) windows against various orientations. Double-glazed windows have an extremely low U value, allowing less heat to enter the building. Whereas the west and south orientations produce the best U value of 0.401 W/m^{2}K, the east orientation produces a U value of 0.400 W/m^{2}K, and the north orientation produces a U value of 0.399 W/m^{2}K. Single-glazed windows have higher U values in different orientations. The U value for the west and south orientations is 3.946 W/m^{2}K, 3.97 W/m^{2}K for the east orientation, and 4.003 W/m^{2}K for the north orientation. Because of the enormous amount of heat entering the building, a high U value will increase electricity consumption. This is because single-paned windows are used. So, instead of single-paned windows, choose double-paned windows, which have been shown to be more successful at reducing heat in buildings. This is because the gap slows down the movement of heat through the window. This results in a lower transmittance value, as less heat is able to pass through the window. This conclusion is supported by the thermal resistance value. A double-glazed window has higher thermal resistance than a single-glazed window at any orientation. A high thermal resistance indicates a good insulating system Whereas the west and south orientations may resist the indoor heat by 2.49 K/W, the north orientation can resist the indoor heat by 2.502 K/W, and the east orientation can resist the indoor heat by 2.497 K/W. It indicates that the north orientation is best suited for insulation purposes.



(a)

(b)

FIGURE 11. Cumulative thermal resistance and U value of double-glazed (a) and single-glazed (b) window against various orientation

CONCLUSION

In this simulation, heat transfer in a semi-transparent PV and double-glazed window was studied using Comsol Software. The PV is made from amorphous silicon solar cells. Various simulations were conducted to model the heat transfer across the double-glazed enclosure and calculate the U value, the electrical energy output, and the thermal efficiencies. The results show that it is possible to reduce the energy consumption of artificial lighting and air-conditioning using appropriate control systems and furthermore to generate energy using semi-transparent photovoltaic panels in windows. The use of semi-transparent PV and double- glazed window has proven to be more effective in reducing heat transfer in buildings and generating electricity. The main conclusions of the present analysis are as follows:

1. The north orientations provide the lowest U values and the greatest thermal resistance.
2. In December, PV cells have the highest efficiency for each orientation. In this month, the west and south orientations provided the greatest U value.
3. The north orientation has the highest cell efficiency but generates the least amount of electricity. When compared to other orientations, the east orientation produces the most electricity.

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DECLARATION OF COMPETING INTEREST

None

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