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Passive Window Energy Performance in Buildings: Modeling of Apartment Buildings in Indonesia

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ABSTRACT

Along with urban growth in urban areas and energy consumption, which continues to increase every year, the selection of windows in the initial design is essential to obtain buildings that are not energy intensive. Selecting the correct window in the blueprint design reduces building energy consumption. Smart windows, especially thermochromic windows, are one of the most promising window technologies because they are the most economical and have passive control with zero energy input, which holds good promise for energy-saving applications. Apart from that, double-glazing windows are also frequently used in energy-saving applications. Therefore, a study compared the energy-saving potential of thermochromic and double-glazing windows to clear glass windows, using computer modeling through EnergyPlus, in high-rise apartment buildings in cities throughout Indonesia's diverse climates. From the modeling results, total energy consumption can be reduced by around 8.91% to 10.96% of total building energy consumption by replacing the conventional clear glass with double-glazing windows or more able to reduce about 20.22% to 24.19% by replacing the conventional clear glass with thermochromic windows. Furthermore, this potential varies depending on geometric shapes, materials, building facades, local climate, and building orientation. Nevertheless, considering the potential benefits, these windows are highly suitable for application in buildings seeking to reduce their energy consumption and improve energy efficiency.

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1. INTRODUCTION

Building is one of the economy's most dynamic sectors and significantly contributes to development [1]. Building growth is increasing in various urban areas in the world, especially in developing countries, to meet the needs of the population's housing infrastructure [2]. In its development, many stakeholders agree that multi-story housing is a good option for providing a more sustainable form of housing. Jakarta, one of the most populated cities in Southeast Asia, has 28,766 apartment units in 183 blocks and 51 towers, with an occupancy value of 98.31% of the total tower capacity in 2020 [3]. The choice of apartments and flats, which have become popular recently, is due to their less land consumption, less resource consumption, and better accessibility [4], [5]. Therefore, considering efforts to use energy more efficiently becomes one of the essential things.

The building sector is responsible for 36% of final energy consumption and more than 55% of electricity demand [6]. In addition, buildings are responsible for more than 39% of energy-related carbon dioxide (CO_2) emissions [6]. In addition, in tropical climates, the energy use of HVAC systems can approach 50% of the energy use of a whole building [7], [8]. For this reason, energy efficiency has become a critical issue due to energy dependence and social and economic development.

Various ways have been developed to improve energy efficiency in buildings through adjustments to building architecture, use of energy-efficient technologies, reduction of energy consumption in operations, and application of renewable energy. Passive design methods such as insulation materials, glass coatings, shading devices, and green roofs are viable options for reducing carbon dioxide emissions [9]. In addition, using insulation materials for windows can be developed as an energy-saving technology. This technology minimizes significant thermal losses by optimizing natural lighting because the configuration of the facade openings, including windows, substantially influences the energy consumption of the building as a whole [10]. Besides that, the most energy-sensitive part of the building envelope is one of the crucial elements that affect the energy consumption of a building [11].

In overcoming these problems, various smart Windows technologies can be the solution. Smart windows enable adaptive and controllable features that adjust their optical properties in response to changing boundary conditions, improving energy performance and building user comfort. According to several previous studies, the use of smart windows in buildings can reduce energy consumption by up to 10–30% when compared to windows with operable blinds and up to 50–75% when compared to windows without blinds [10], [12]– [16]. There are two main types of smart windows: active smart windows and passive smart windows. Active smart windows are those that require an external power source to function. They use electrochromic, thermochromic, or photochromic materials to change their opacity, color, or light transmission when a voltage or current is applied. For example, electrochromic windows use an electrical charge to change the color of the glass, making it darker or lighter as needed. Active smart windows are more expensive than passive smart windows because they require additional components, such as sensors and control systems.

On the other hand, passive smart windows do not require an external power source to function. They use materials that can change their properties due to environmental factors, such as temperature or light. For example, thermochromic windows change color in response to temperature changes, and photochromic windows darken when exposed to sunlight. Passive smart windows are more affordable than active smart windows and require less maintenance since they do not have any electrical components [17].

Of the various existing technologies, thermochromic windows are one of the technologies that have been developed and are considered more effective in saving energy than other windows because of their nature as passive windows that do not require electricity [18], [19]. In addition, because of its passive and energyless input nature, thermochromic is considered the most economical and rational chromogenic technology for stimulation [18], [20]. In several previous studies, thermochromic windows were reported to have the potential to save heating and cooling energy requirements from 5.0 to 84.7%, compared to ordinary glass, with saving values that varied in each climate and condition [15], [18], [21], [22], including some carried out in a tropically hot and humid environment, and provides promising savings potential as well by preventing heat entrance [23]–[27]. Therefore, this study analyzed buildings' energy requirements to select window types. This selection involves three types of windows, namely clear single glass pane, double glass pane, and compared with thermochromic windows. This study raises the case for the multi-story apartment building model and focuses on the weathering profile in various big cities in Indonesia.

2. RESEARCH METHOD

2.1 Passive Window Characterization

In this study, three types of window glass represent passive windows: single-pane, double-glazing, and thermochromic glass. The single-pane window is the standard type of window glass used in homes and buildings, especially in developing countries [28]. It allows visible light to pass through but has a low insulation value, making it less energy efficient. Lack of awareness of energy saving and the high cost of renovating or procuring front windows means that single-pane windows are still widely used. On the other hand, double-glazed windows have two layers of glass separated by a gap filled with air or gas, making them much more energy-efficient than single-pane windows. They also help to reduce outside noise and prevent condensation. Thermochromic glass is a type of glass that changes color in response to changes in temperature. It can help regulate the temperature inside a building and reduce the need for heating and cooling systems. The description of the window model and the characterization of each window used are explained as follows.

2.1.1 Window Modeling

The single-pane window used in this calculation uses clear glass with a thickness of 8 mm. The double-glazing window used in this calculation consists of a double-pane window with a 4 mm clear glass thickness flanking a 12 mm gap filled with air. This model is shown in Figure 1.

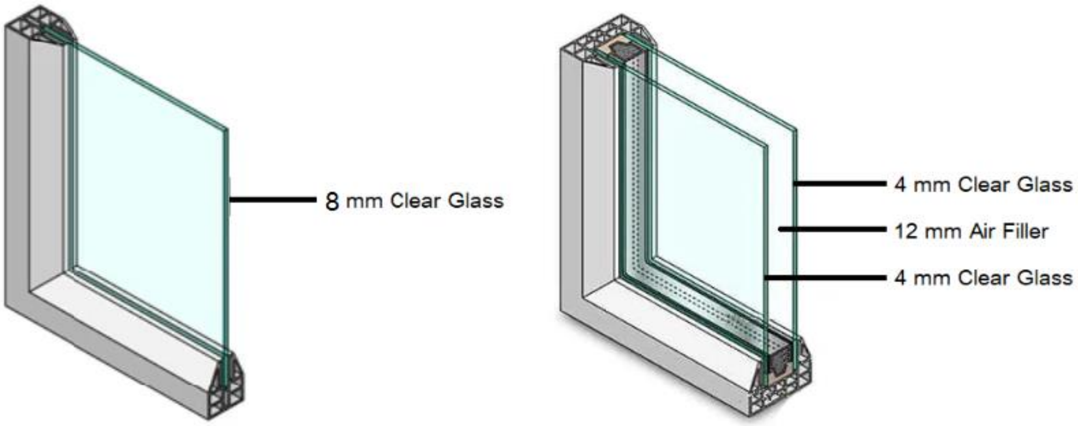


Figure 1. Single And Double-Glazing Window Models Were Used in This Study.

In addition, one type of smart window technology was used in this study, namely, a thermochromic window. Thermochromic is a reversible process of changing the color of materials due to temperature changes, usually switching between a clear state at low temperatures and a dark state at high temperatures [18], [20]. A thermochromic color change does not occur due to a change in the phase of the material but due to a change in the chemical structure of the material or the physical structure of the material. The working process of this thermochromic window is described in Figure 2.

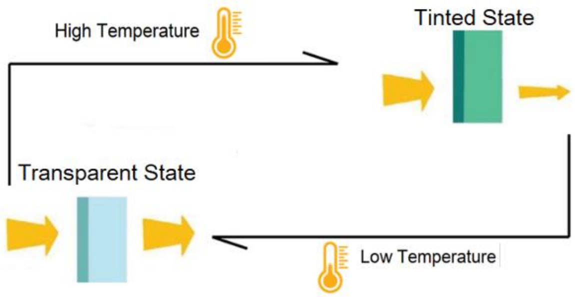


Figure 2. The Working Mechanism of Thermochromic Windows.

In this study, the thermochromic window model was adapted based on the ideal vanadium oxide (VO_2) based thermochromic window model developed by Yang et al. (2015) [29]. In this model, when the temperature of the film is below or above the phase transition temperature, the film is immediately in a semiconductor (unconscious state) or metallic (hot state) state. This model is illustrated in the graph of the relationship between temperature and transmittance of VO_2 films in Figure 3.

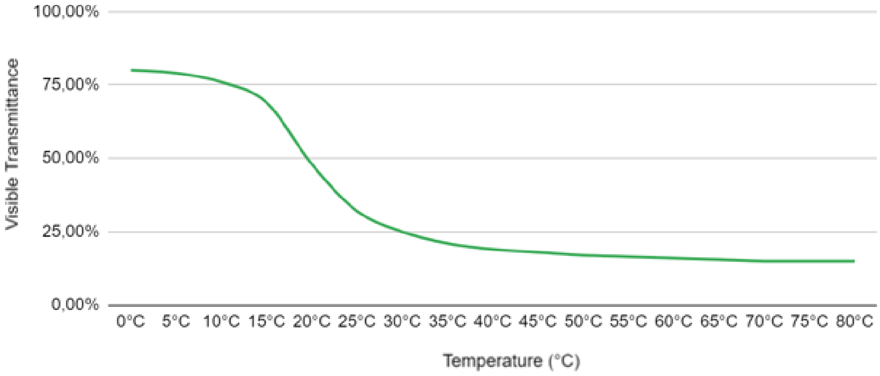


Figure 3. Graph Of The Correlation Between Temperature and Transmittance Shown in The Ideal Thermochromic Model Based on Vanadium Oxide [29].

2.1.2 Window Optical and Thermal Properties

The window has optical and thermal properties to describe its performance. A comparison of the optical properties between the various types of windows is shown in Table 1. Some of the optical properties of these windows include visible light transmittance, UV blocking, and infrared blocking. While the thermal properties of the window include U-value, Solar Heat Gain Coefficient (SHGC), and Light Solar Gain Ratio (LSG), a comparison of these parameters in the three windows is shown in Table 2.

Table 1. Comparison of optical properties between the three windows used in this modeling [29]–[31].

No	Parameter	Single-Pane	Double-glazing	Thermochromic
1	Visible Light Transmittance	0.88	0.82	0.80 (0°C) ~ 0.15 (80°C)
2	UV blocking	62%	81%	99~100%
3	Infrared blocking	0.11	0.23	0.16

Table 2. Comparison of the thermal properties between the three windows used in this modeling [29]–[31].

No	Parameter	Single-Pane	Double-glazing	Thermochromic
1	U-value	5.8 W/m²K	2.9 W/m²K	2.7 W/m²K
2	Solar Heat Gain Coefficient (SHGC)	0.81	0.77	0.11 (0°C) ~ 0.32 (80°C)
3	Light Solar Gain (LSG) Ratio	1.09	1.06	7.27 (0°C) ~ 0.47 (80°C)

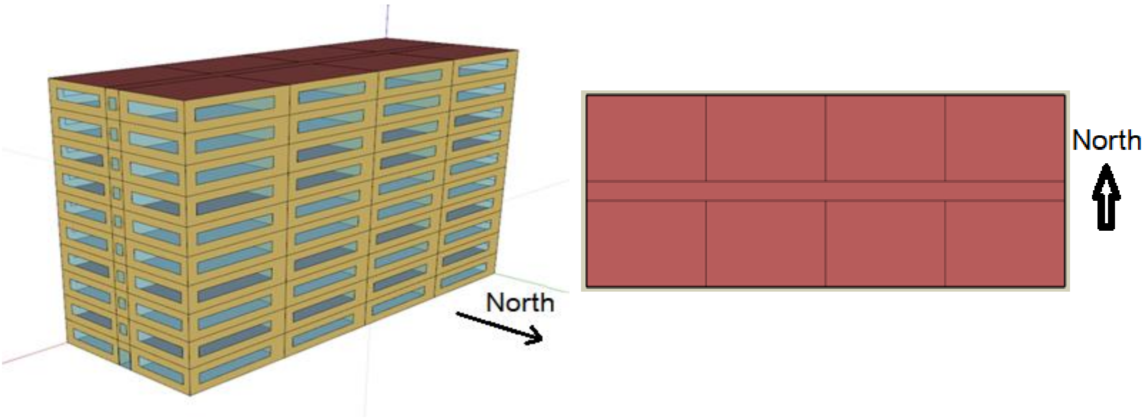
2.2 Building Energy Consumption Modeling

2.2.1 Building Description

EnergyPlus software version 9.6.0 simulates energy demand and potential energy savings. Modeling using EnergyPlus has been widely used to model energy consumption in buildings, including taking into account differences in material and window technology [23], [26], [32]–[35]. EnergyPlus is open-source software that can simulate building energy used to model energy consumption, lighting, plug and process loads, and building water use. The EnergyPlus app has 16 control parameters, including incident solar radiation, outdoor temperature, daylight exposure, etc. EnergyPlus can develop custom control and modeling routines using an Energy Management System (EMS).

The building model used in this study uses an apartment building by ASHRAE 90.1-2004 and is available in the Prototype Building Model Specifications developed by the Pacific Northwest National Laboratory [36]. This multi-story apartment building prototype consists of 10 floors with eight rooms on each floor, except for the 1st floor, and there is a corridor in the middle, as shown in Figure 4.

The multi-story apartment building used in this model has a total area of 7,836.48 m^2, stands at 0 degrees north, and is not altered in this study. This building has a window-to-wall ratio of 30%. The HVAC system in this building uses a constant-volume water-sourced heat pump. In this study, the limitation is given by only looking at variations in the type of glass technology on energy consumption so that other parameters such as building orientation, windows-to-wall ratio (WWR), building construction materials, and working conditions are identical and similar for each case.



(a) (b)

Figure 4. Building model prototype simulation (a) Building shape (b) Thermal zone.

2.3 Climate Profile

The climate profile used in this modeling is based on dry-bulb temperature, percent humidity, wind speed, and direct and diffuse solar radiation. Dry-bulb temperature refers to the air temperature measured by a thermometer that is not affected by moisture or humidity. It is commonly used to estimate human thermal comfort, building energy demand, and outdoor conditions. Percent humidity is the amount of moisture in the air relative to the amount it can hold at a given temperature. High humidity levels can increase heat and discomfort, while low humidity levels can cause dry skin, throat irritation, and other health problems. Wind speed is the movement of air relative to the Earth's surface and is measured in miles per hour or kilometers per hour. It can impact human comfort, outdoor activities, and the dispersion of air pollutants. Direct and diffuse solar radiation are the two main components of solar energy that reach the Earth's surface. Direct radiation is the sunlight that arrives at the surface without being scattered or absorbed by the atmosphere. Diffuse radiation is the sunlight scattered by the atmosphere and reaching the surface from all directions. They can influence the temperature and lighting conditions of outdoor environments and affect the performance of solar energy systems. As a comparison of how the climate profile in each region is modeled, the annual average dry bulb temperature data from various cities modeled in this study are shown in Table 3. It is usually calculated by adding the daily dry-bulb temperatures for the entire year and dividing the sum by the number of days.

Table 3. Annual average dry bulb temperature statistics from 2004-2018 [37].

Location	Annual average dry bulb temperature (°C)		
	Highest	**Lowest**	**Daily Average**
Jakarta	39,1	17.0	28.4
Surabaya	35.5	20.0	27.6
Semarang	36.2	20.4	28.2
Manado	33.3	16.5	26.2
Pontianak	25.0	22.0	26.9
Jambi	33.8	17.6	26.8
Medan	34.8	16.0	27.7
Pekanbaru	38.0	20.0	26.7
Bandung	32.8	9.3	22.2
Denpasar	33,0	19,6	27,5

3. RESULTS AND DISCUSSION

3.1. Energy Saving Potential

Based on statistical data obtained through modeling using EnergyPlus, the potential for reducing energy consumption is obtained from double-glazing and thermochromic windows compared to single-pane windows (clear glass). Here, the average energy consumption is calculated as the arithmetic mean of all the simulations performed for each city. Based on this modeling, the total amount of primary energy required to operate a building, including the energy used to generate and distribute the electricity, natural gas, or other fuels that the building consumes (source energy) per building area (MJ/m^2) is obtained, as shown in Figure 5. The method for calculating source energy, for example, if a building consumes 100 units of electricity and the energy conversion and transmission losses for the grid are 40%, the source energy would be 100/0.6 = 166.7 units of primary energy. Similarly, if a building consumes 50 units of natural gas and the energy conversion and distribution losses are 20%, the source energy would be 50/0.8 = 62.5 units of primary energy.

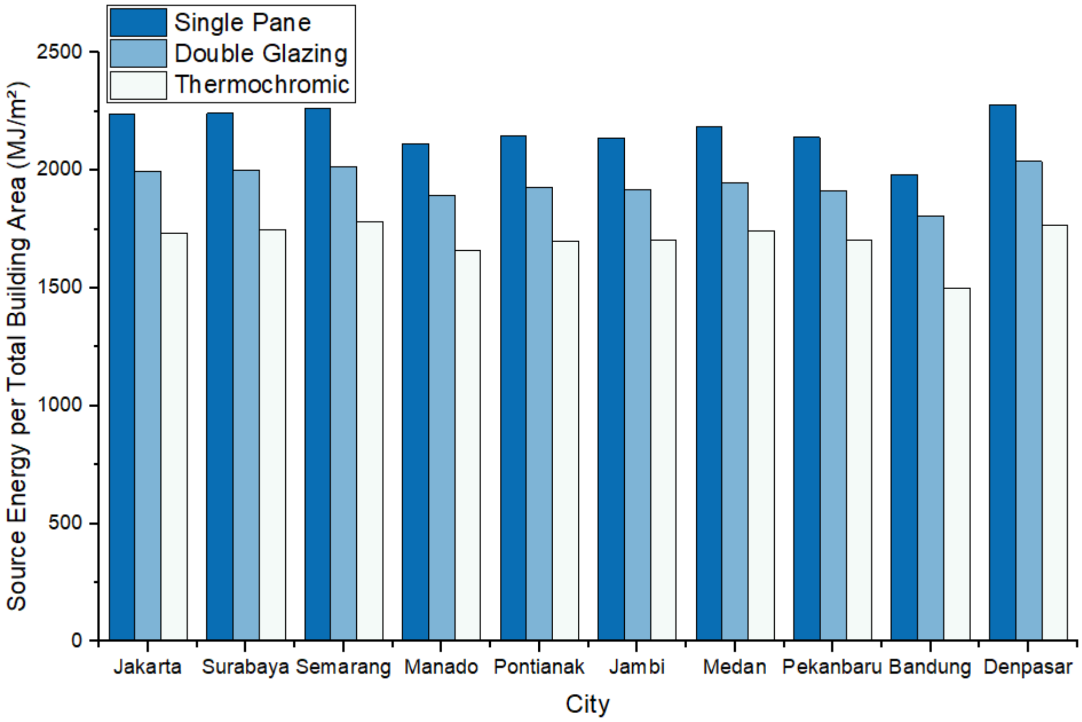


Figure 5. Comparison of Source Energy Per Total Building Area in Various Cities in Indonesia

Despite the difference in absolute values for energy use between the two models (double glaze and thermochromic), the overall energy savings of different window technologies and potential energy-saving trends are comparable. This decrease in energy consumption is seen in all the building models studied. The results of this energy reduction can be seen in Figure 6.

According to the results of the modeling carried out, the total energy consumption can be reduced by around 8.91% to 10.96% of the entire building's energy consumption by replacing the conventional clear glass with double-glazing windows, or more capable of lowering around 20.22% to 24.19 % by replacing the conventional clear glass with thermochromic windows.

In Jakarta, modeling results show savings of 10.85% and 22.73%, respectively, for savings from double-glazing and thermochromic windows over clear glass. The results obtained are similar to the results of modeling in other cities on the north coast of Java, where the potential savings are 10.21% from using double-glazing windows and 21.99% from using thermochromic windows in Semarang, as well as saving 10.88% and 21.18% from the use of double-glazing windows and 21.99% from thermochromic windows in Surabaya. The profile of potential savings in these three cities is relatively the same because the local climatic conditions of the three regions tend to be the same on the north coast of Java.

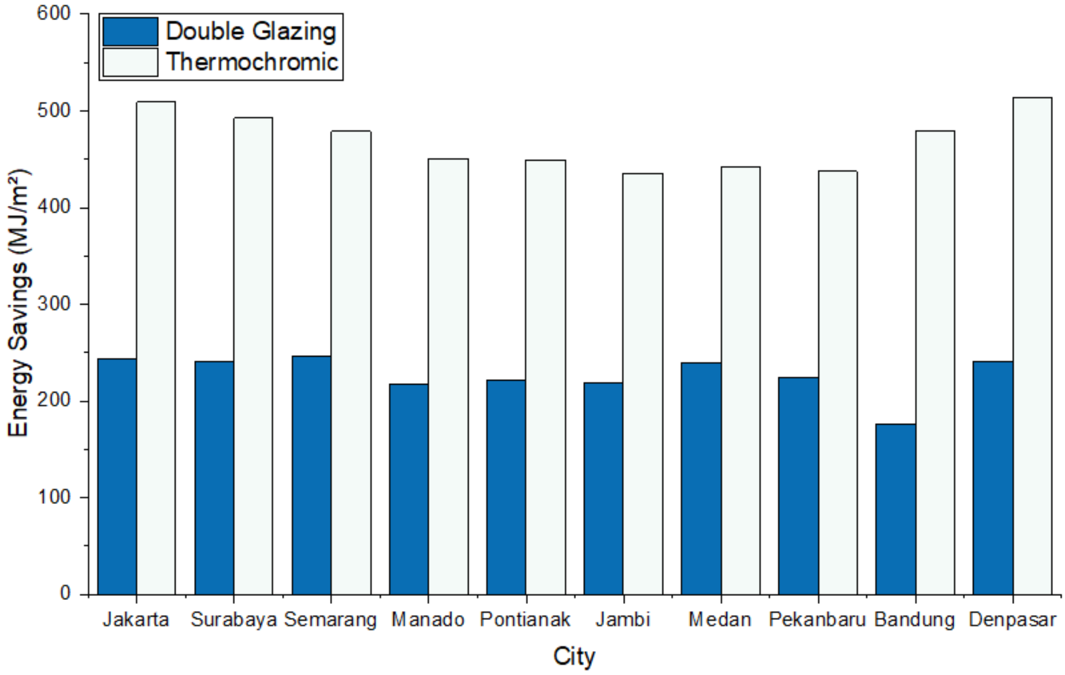
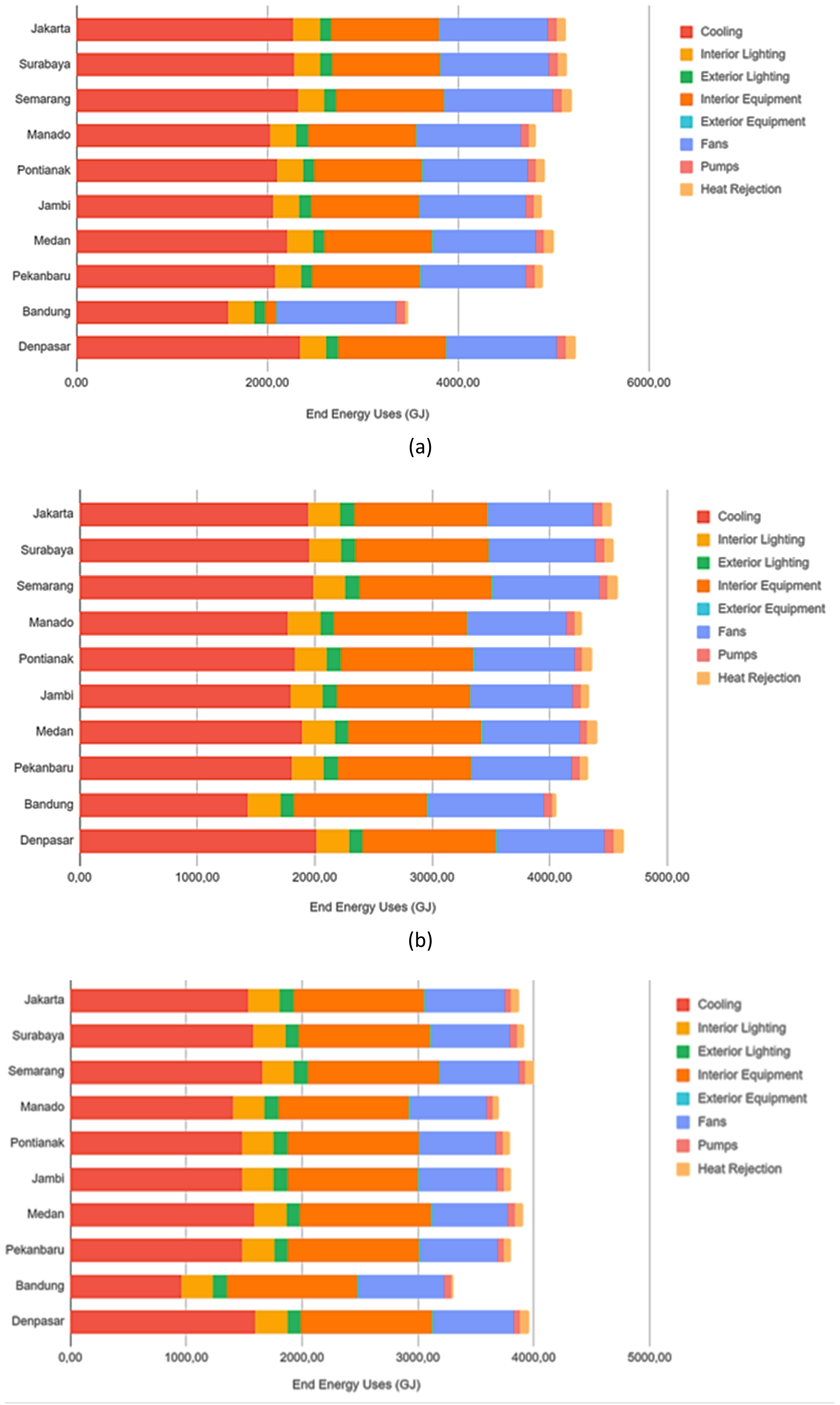


Figure 6. Comparison Of Energy Savings Using Double-Glazing and Thermochromic Windows In Various Cities In Indonesia.

This result is different from cities in Java Island which are in hilly areas which in this case is represented by the City of Bandung, where the energy saving potential is 8.91% from the use of double-glazing windows and 24.19% from the use of thermochromic windows. The use of the thermochromic window represents the most significant saving potential of the thermochromic window studied in this paper. On the other hand, the potential for energy savings from double-glazing windows in this city shows the smallest potential savings compared to other cities due to this region's relatively cold local climate conditions.

While modeling in other cities in Indonesia is also quite varied, research in Manado shows savings of up to 10.33% from double-glazing windows and 21.36% from thermochromic windows. In other cities, Pontianak shows savings of 10.32% from double-glazing windows and 20.90% from thermochromic windows. Jambi is also modeled in this study, featuring savings of up to 10.25% from double-glazing windows and 20.36% from thermochromic windows. A survey in Medan showed savings of up to 10.96% from double-glazing windows and 20.22% from thermochromic windows. In Pekanbaru City, savings reached 10.50% from the use of double-glazing windows and 20.45% from the use of thermochromic windows. Meanwhile, research in Denpasar, Bali, showed savings of up to 10.42% from double-glazing windows and 22.57% from thermochromic windows.

Furthermore, the breakdown of energy consumption for several cases in this modeling is shown in Figure 7. Based on the results of this model, the primary energy load in cities in hot, humid, and tropical regions is for air conditioning systems, as found in most cities in Indonesia. In this case, it is assumed that indoor residential activities are similar according to the operational needs of the building, which are highly dependent on building functions and the behavior of end users.



(a)

(b)

(c)

Figure 7. Final Energy Use (GJ) of the Total Building Area Using (A) Single-Pane Windows, (B) Double-Glazing Windows, and (C) Thermochromic Windows.

In the model studied, the cooling system is the largest consumer of the total building energy consumption, the value of which varies depending on each local climate. Buildings with single-pane windows consume the highest cooling energy, ranging from 1,585.65 GJ in Bandung to 2,344.70 GJ in Denpasar. The high consumption of cooling energy is due to the poor insulation of single-pane windows, which allow a lot of solar heat to enter the building, thereby increasing the cooling load.

Using energy-efficient windows like double glazing and thermochromic windows can significantly reduce building cooling energy consumption. The data shows that after installing double-glazed windows, cooling energy consumption decreased from around 1,432.45 GJ in Pekanbaru to 2,015.45 GJ in Denpasar. Meanwhile, buildings with thermochromic windows have lower cooling energy consumption, ranging from 954.82 GJ in Bandung to 1,656.08 GJ in Semarang. Due to double-glazed and thermochromic windows, low energy consumption provides better insulation and solar control, which reduces the amount of solar heat entering the building and the need for mechanical cooling.

Based on this study, it is worth noting that the energy consumption of other building components, such as interior and exterior lighting and equipment, was not affected by the type of glass used. In this study, the energy consumption of interior lighting was assumed to remain constant and automated due to sufficient daylighting. This energy-efficient strategy utilizes natural light to reduce the need for electric lighting. Therefore, the simulation considered the interior lighting energy consumption values constant. Similarly, the energy consumption of exterior lighting and equipment was assumed to remain consistent as the type of glass used did not affect their energy consumption.

In addition to cooling energy, changing the type of glass in buildings can also affect the energy consumption of fans, pumps, and heat rejection systems. The type of glass affects the amount of heat and light that enters the building, which can, in turn, affect the temperature and humidity levels inside. The different values of energy consumption for fans, pumps, and heat rejection systems in the different types of glass can be seen in the data provided, with each city having its range of values. In buildings with single-pane windows, the energy consumption of fans ranges from 1,071.60 GJ in Medan to 1,241.22 GJ in Bandung. Similarly, the energy consumption of pumps goes from 85.91 GJ in Pekanbaru to 92.92 GJ in Bandung. In comparison, the energy consumption of heat rejection systems ranges from 32.86 GJ in Bandung to 99.99 GJ in Semarang.

After replacing single-pane windows with double-glazed windows, energy consumption is significantly reduced across all three systems. The energy consumption of fans ranges from 821.23 GJ in Medan to 978.45 GJ in Bandung, while the energy consumption of pumps ranges from 66.72 GJ in Medan to 74.55 GJ in Bandung. Similarly, the energy consumption of heat rejection systems goes from 30.34 GJ in Denpasar to 89.63 GJ in Semarang. Furthermore, thermochromic windows show an even more considerable reduction in energy consumption compared to single-pane and double-glazed windows. The energy consumption of fans ranges from 650.75 GJ in Medan to 735.39 GJ in Bandung, while the energy consumption of pumps ranges from 54.46 GJ in Semarang to 57.70 GJ in Denpasar. Similarly, the energy consumption of heat rejection systems ranges from 21.36 GJ in Bandung to 73.19 GJ in Semarang.

Furthermore, replacing single-pane windows with energy-efficient windows can significantly reduce energy consumption for fans, pumps, and heat rejection systems. Double-glazed windows reduced energy consumption compared to single-pane windows, and thermochromic windows demonstrated an even more considerable reduction. The energy savings from using energy-efficient windows can result in significant cost savings for building owners and operators and reduce the building's environmental impact.

Therefore, when choosing glass for buildings, it's important to consider the energy performance of each option. Double-glazed windows are more energy-efficient than single-pane windows. Double glazing can reduce the cooling load of a room, leading to less energy consumption from cooling systems such as fans, pumps, and heat rejection systems. Similarly, thermochromic windows are even more efficient than double-glazed windows. These windows are designed to adaptively absorb incoming heat, reducing the need for cooling systems altogether. By being transparent at low temperatures and opaque at high temperatures, thermochromic windows provide a spectrum of light and heat that can enter the room while minimizing energy consumption.

Thermochromic and double-glazing windows have shown promising potential for energy savings in buildings. However, this potential varies depending on various factors such as geometric shapes, materials, building facades, local climate, and building orientation. Therefore, it is essential to consider these factors when applying these windows in a building. Nevertheless, considering the potential benefits, these windows are highly suitable for application in buildings seeking to reduce their energy consumption and improve energy efficiency.

Besides that, the use of double-glazing provides two opposing points of view in different areas, where the installation of double-glazing in cold climates has the effect of heat being trapped indoors so that heat from outside cannot enter the room, so there is an increased need for a cooler room. It should not be required in buildings in cold climates, which implies increased energy requirements. Meanwhile, double-glazing installation in hot climates can reduce the cooling load of the room by keeping the room cool even though it is hot outside. Meanwhile, on the other hand, thermochromic windows provide better performance in both conditions by reducing energy requirements for the cooling system. Its performance can adaptively absorb incoming heat by being transparent at low temperatures and opaque at high temperatures, providing a spectrum of light and heat that will enter the room.

4. CONCLUSION

Double-glazing and thermochromic windows have been modeled to achieve an energy-efficient profile compared to single clear glass windows. The model was developed in a high-rise apartment building at EnergyPlus and is simulated in various city profiles in Indonesia. From the modeling results, total energy consumption can be reduced by around 8.91% to 10.96% of total building energy consumption by replacing the conventional clear glass with double-glazing windows or more able to reduce about 20.22% to 24.19% by replacing the conventional glass and clear glass with thermochromic window. Double-glazing and thermochromic window use can significantly reduce cooling energy, fans, pumps, and heat rejection system energy. Using double-glazing and thermochromic windows can lead to a substantial reduction in cooling energy usage, as well as the energy consumption of fans, pumps, and heat rejection systems. Furthermore, this potential varies depending on geometric shapes, materials, building facades, local climate, and building orientation.

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