JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

Investigation of the Effectiveness of the Modeling on the Glazed Window by Energy Simulation using EnergyPlus, Case study: Phnom Penh City, Cambodia

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Abstract: The leakage of air cooling through transparent facades and the transfer of solar radiation through glazed windows have led to increased energy consumption in buildings. To address this issue, a concept has been proposed wherein a fully glassed-in facade acts as the building envelope, resulting in energy savings on air conditioning. Glazing plays a crucial role in daylighting, thermal comfort, and heat transfer between indoor and outdoor spaces. To enhance glazed windows for solar protection and energy efficiency, there are two approaches: applying film coatings to existing windows or replacing single-glazed windows with double-glazed alternatives. In this research, we aim to investigate the energy-saving potential of these approaches using energy simulation through EnergyPlus. For this case study, we utilize the OpenStudio SketchUp Plug-In, an interface software introduced through the United States Department of Energy. Our simulated results demonstrate that the addition of film coatings to existing glazed windows effectively reduces energy use. The amount of energy savings depends with the color of the film coating. which should range between 2.50% and 0.61%. Additionally, replacing single-glazed windows with double-glazed alternatives yields positive results, with a simulation error not exceeding 1.78%. It is crucial to note that economic outcomes for individuals may significantly vary from those discussed in this research due to factors such as diverse wall and roof types, climate variability, and occupant habits. These variables contribute to diverse outcomes beyond the scope of this study.

Index Terms – OpenStudio, EnergyPlus, Residential Building, Energy Efficiency, Energy Simulation.

I. Introduction

As the emphasis on environmental responsibility and efficient energy consumption continues to shape building design goals, the construction sector remains reliant on the use of electric power and heat [1]. Cambodia, being a developing country with a rapidly growing population, faces notable challenges, particularly concerning the widening gap between environmental sustainability and energy consumption in residential buildings. In 2019, Cambodia's population was 15,552,211, with an anticipated annual growth rate of 1.4% [2]. Projections suggest that residential building construction in Cambodia has witnessed a significant increase, with an approximate rise of 34%. In 2020, there were 21,074 flats, and this number further grew to 31,984 flats by 2021 [3]. Consequently, the escalating demand for energy and its consumption has emerged as a critical environmental concern. The residential building energy consumption in the electricity sector accounted for around 19.4% of Cambodia's total energy consumption in 2018 [4], signifying a substantial 24% increase compared to the previous year's energy consumption.

The windows are not only an integral component of a building, enhancing its aesthetics and facilitating the flow of natural light and fresh air for the utmost comfort of occupants, but they also significantly impact the energy efficiency of the structure. The design of windows has a substantial impact on the interior condition (heating and cooling load) of the residential building with energy consumption (on a building's energy use for heating and cooling), as they account for a significant portion of heat input or loss through the building envelope [5], and that windows contribute to approximately 25–30% of heat exchange in residential buildings due to the not-included insulating layer on the glazed window properties [6]. The category of panel with a lower heat transmission ratio is directly linked to increased energy consumption [7]. When choosing windows that are suitable for specific climates, modern options provide users with valuable insights into crucial performance factors. These factors play a vital role in differentiating window efficiency and enable security agencies to make well-informed decisions regarding window selection and energy management during installation. The study primarily focuses on three key variables: the sunlight's factor, U-factor, and optical transparency, as they are considered essential aspects of window performance. These variables encompass various factors that contribute to the overall effectiveness of windows.

Many authors have conducted extensive research on the effectiveness of windows. Key features encompass the capability to incorporate spectral or spectral-averaged glass reflectivity, account for solar and visible transmission as a function of incidence angle, simulate the heat balance solution to ascertain glass surface temperatures, compute heat transfer within frames and separators, and model adjustable interior or exterior shading systems with customizable controls [9]. The test outcomes demonstrated the efficacy of diverse window configurations across varying conditions and building typologies. The energy efficiency of windows and angle-resolved optical characteristics [9]. In this research focus on a theoretical assessment of the optical and thermal characteristics of windows is evaluated, as well as the energy efficiency of a wide range of windows, under different conditions, and Simple models for predicting angle dependence have been compared, using both theoretical and measured real window glazing's. It has been determined that the influence of inaccurate angle dependency of the U-factor is apparent but not necessarily important.

Other researchers have investigated the effectiveness of additional film coatings on glazed windows by measuring and comparing the glass surface temperatures of various solar window film applications with those of similar window glass types without solar window films [10]. Their research primarily focuses on experimental validation and utilizes computer models to assess sunlight panel film's possibility of energy conservation samples when applied to the glazing of different functional areas in Hong Kong, such as offices, retail malls, and hotel guest rooms. The findings demonstrate that the application of solar films can result in significant reductions in energy consumption across all three commercial building areas, with office settings showing the highest energy-saving outcomes. Furthermore, another study has examined the precise thermal diffusion (U-value) and SHGC values for various window glazing materials, as well as the potential energy savings offered by various commonly available window panes [11]. This research evaluates the capacity of various window glass types, including coated, reflecting, glasses with single and double glazing, to conserve electricity. The study emphasizes with significance that considering the U-factor and sunlight values when carefully selecting appropriate window glazing. Additionally, it highlights that retrofitting different commercially available window glasses can lead to roughly equal reductions in electrical energy consumption compared to the base building.

Double-glazed windows are widely recognized as a crucial component of procedures for reducing electricity within the building's exterior. Researchers have conducted studies to examine the impact of various glazing platforms, from single-glazed transparent windows to double-glazed, on the sun's heat absorption and cooling demand of the window with electro-chromic reflecting colored glass [12]. The findings indicate that properly oriented glazing systems can effectively reduce solar heat gain, lower cooling demand, and enhance thermal comfort. Various window glazing methods have been explored to maximize energy savings in buildings and homes [13]. One approach involves double-glazed windows should be utilized as opposed to traditional single-glazed panes, followed by the implementation of triple-glazed windows. Additionally, combining panels with double glazing and lighting level with high-quality utilization can further enhance energy efficiency. The results demonstrate that glazed window twice is particularly well-suited for environment in India, showcasing their effectiveness to improving energy efficiency.

The existing models developed prior to the introduction of modern innovations such as suction glazing and the protection of the exterior coatings, may need to be reassessed in light of these advancements [14]. For this research, the methodology relies on energy calculations performed using EnergyPlus, a widely recognized and utilized tool for building energy assessments worldwide [15]. EnergyPlus enables the modeling of various energy flows, including heating, cooling, lighting, ventilation, and building water circulation. It serves as a comprehensive implement for energy simulations, capacity calculations, inspections and evaluations of residential buildings, heat and mass balance analyses, and is classified as one of 375 programming devices dedicated to assessing building sustainability, sustainable energy, and energy performance. EnergyPlus can be downloaded free of charge from the official website [16]. Developed through a collaborative effort involving the U.S. Department of Energy (DOE) and six other organizations, EnergyPlus was selected as the simulation tool for this study due to its global support, extensive capabilities, and abundant resources available for energy consumption estimation. In addition to EnergyPlus, other Building Information Modeling (BIM) simulation applications, such as Ecotect, EnergyPlus, and Transys, can effectively evaluate energy consumption in buildings [17, 18, 19].

II. RESEARCH METHODOLOGY

The This study focuses on analyzing the impact of various types of double-glazed windows and film coatings, commonly used in Cambodia, on annual energy consumption. The primary objective of the research is to address residential retrofitting for energy savings, with a specific goal of presenting three simulation options for an apartment building. The research aims to quantify the potential energy savings and involves a comprehensive evaluation of yearly energy consumption. This evaluation compares simulation results from multiple scenarios with the actual annual energy consumption data, enabling a thorough assessment of energy-saving potential.

This study encompasses the following key objectives:

- Investigating the feasibility of enhancing the energy performance of existing glazed windows through the application of an additional film coating.
- Comparing the energy performance characteristics of double-glazed windows with the existing single-glazed windows.
- Analysing the potential benefits of selecting specific colours for the film coating, which can contribute to energy savings in residential buildings and enhance overall energy efficiency.

2.1 General Information of the flat building

In practice, it's important to note that every geographical location mentioned in this article exhibits unique differences in the quantity, dimensions, and makeup of windows, along with variances in the materials used for the building envelope. However, within the scope of our research, we concentrated on a consistent organization but explored various glazing systems to evaluate their influence on energy use. To examine energy efficiency in a building located in Phnom Penh, Cambodia, a specific residential building was selected as a model for energy consumption simulation. The flat building was constructed in 2019 but occupied for the first time in 2020.

The flat building represented in this study is a two-story building with a floor area of 41.8 m^2 and a height of 6 m, and the rooftop is the slope constructed using reinforced concrete, and the windows cover approximately 1.8% of the building's surface area. The building structure was implemented in OpenStudio as two-thermal conditions, with outside dimensions of 14.66 m x 4 m. The first floor includes two windows measuring 0.6 m x 1.20 m and 2.25 square meter on each of its walls.

The building is positioned in a row configuration, featuring internal walls that expose both the front and rear facades to external elements such as weather conditions, sunlight, wind, etc., as depicted in Figure 1. The ground temperature is adjusted to closely match the local ground temperature, and interzone heat transfer is factored in by modeling all interior surfaces. The materials used for the walls, floors, and ceilings are chosen to match those utilized in the actual construction of the modeled residence. The design of each window in the building follows a single glazed system with an aluminum frame.

Internal parameters are set to reflect a household of four individuals with average occupancy levels for residential houses. Electrical equipment is configured with a utilization schedule based on occupancy, must be included with a ground floor load and a first-floor load. The cooling setpoints for the split air conditioner are set at 21 degrees Celsius during the daytime and 24 degrees Celsius during the nighttime. Natural ventilation is considered in this scenario. External conditions are regulated using weather files downloaded from the EnergyPlus website, which provide an annual record of the weather conditions in the specific area, including solar gains, outdoor temperature, etc.

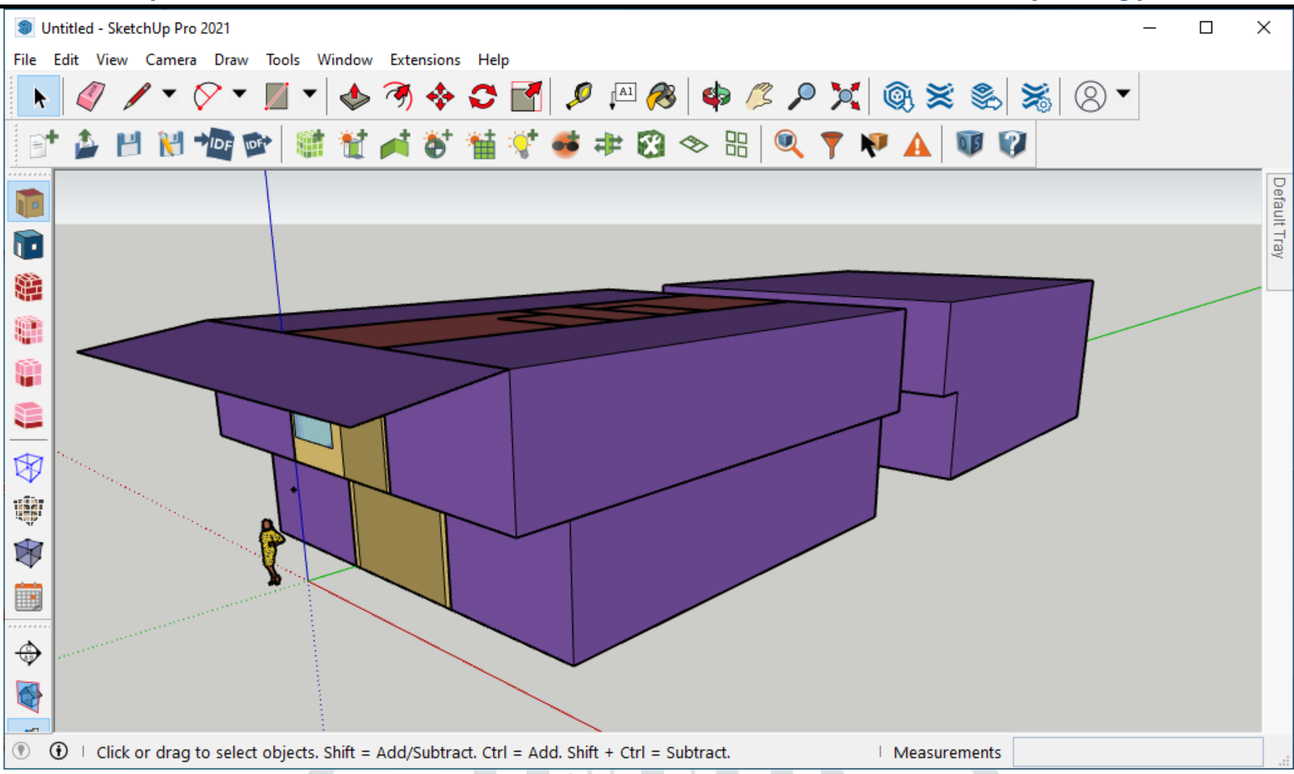


Figure 1. Residential building modeling under investigation

2.2 Specification of Materials Construction

For the building under study predominantly consists of reinforced concrete, while the key components of the building envelope are single hollow brick walls without insulation. The windows installed in the building are fixed glazed windows with clear glazing and a thickness of 3mm, and all energy-efficient glazing options are compared against the Harmonization of Construction Material Thermal Characteristics, Specification Note 91/6 with transparent glass

Table 2. The top portion of the roof is not present in the model.

On both the floor, Single brickwork is used for the walls between the rooms. The composition of the building's interior and exterior surfaces is thoroughly defined. Detailed information is provided regarding the materials used for constructing the walls, floors, ceilings, doors, and windows. The outer layer refers to the layer farthest from the building's interior space, while the internal layer of specified material is adjacent to the zone. A comprehensive description of each building component and the corresponding layer of materials employed in the house is presented in the table below:

Table 1. Mechanical Properties of Construction Materials

Material Properties	Thickness (mm)	Thermal Con. (W/m.k)	Density (kg/m^3)
Hollow Brick[1]	100	0.52	1300
Cement Plaster[1]	15	0.87	1700
Ceiling Board[1]	9.5	0.35	840
Ceramic Tile[2]	8.5	1.05	2200
Reinforced[2]	70	1.55	2400
Wood Door[2]	40	0.35	550
Exterior Glazed[1]	5	0.78	2500
Cement Mortar[1]	60	1.15	1800
Color Paint	0	0	1050
Clay Floor Tile[2]	10	0.85	1900
ESP Insulation[2]	50	0.05	24

[1] National Technical Regulation Energy Efficiency Building, Vietnam: QCVN 09:2013/BXD

[2] The Harmonization of Thermal Properties of Building Materials, Technical Note 91/6.

Table 2. Specification of single-glazed window*

Characteristic	Value
Solar Transmittance	0.88
Outside Solar Reflectance	0.08
Inside Solar Reflectance	0.08
Visible Transmittance	0.91
Outside Visible Transmittance	0.08
Inside Visible Transmittance	0.08
Infra-Red Transmittance	0
Outside Emissivity	0.89
Inside Emissivity	0.89

[*] The Harmonization of Construction Material Thermal Characteristics, Specification Note 91/6

Table 3. Thermal Properties of glazed-window selected for building simulation*

Type of window	Thickness (mm)	U-Value (W/m^2 K)	Visible Trans.	Solar Trans.	SHGC
R15BL SR PS (Blue)	0.042	0.93	9	9	0.22
R15G SR CDF (Gray)	0.042	0.92	6	7	0.23
R15B SR CDF (Bronze)	0.042	0.89	8	8	0.22
DL30 GN SR PS (Green)	0.042	0.99	33	32	0.48
Double glass with Clear	3+12+3	2.7	0.8	0.69	0.76

* Window Film performance data/Architectural North America

2.3 Building Simulation Modeling

The United States Department of Energy's National Renewable Energy Laboratory also developed a user interface for EnergyPlus called Open Studio Plug-in for Google Sketch Up, that allows users to develop and adjust the building geometry for the EnergyPlus input files. The SketchUp 2021 with 3D drawing application does not need to be exited in order to run EnergyPlus simulations or examine the results according to this free plug-in. The plug-in improves the Sketch Up environment with EnergyPlus's building energy simulation capabilities. One can run an EnergyPlus simulation of the model they are currently working on in Sketch Up and view the results without leaving the program, and the capability to generate with modify thermal space and area is one of OpenStudio Plug-in's key features. Open EnergyPlus and check the results without leaving Sketch Up. matching interzone surface boundaries, look up surfaces and subsurface using the object name, include internal gains and basic outdoor air in load calculations, and include the optimum HVAC system.

This means that the buildings, materials, occupancy, internal loads, and schedule were adjusted using OpenStudio, while the geometry, thermal zone, and space type were drawn and created with SketchUp. The method for simulating energy efficiency included a number of steps, starting with modeling the actual building and configuring the parameters in SketchUp and OpenStudio. We created the building geometry, selected the type of space, and established the boundary conditions using SketchUp. The input parameters for OpenStudio can be modified or customized through tabs including the Site tab, HVAC system tab, and Simulation setup tab.

The electricity usage data used for simulation modelling is obtained from Electric du Cambodge (EDC), including the building's annual energy bill for the year 2021. It is noteworthy that the annual energy consumption derived from this data aligns closely with the actual electricity consumption determined through monthly electricity bills.

The research involves an established model of the building, incorporating two specific modifications to evaluate its energy efficiency: Additional Film Coating: An extra film coating is applied to the existing glazed surfaces to enhance their thermal performance. This modification aims to assess the impact of different colors of the energy-saving film coating on energy efficiency. Replacement of Single-Glazed Window: An older single-glazed window is exchanged with a newer model of a double-glazed window. This change enables a comparison between single and double-glazed windows, allowing for an evaluation of their respective effects on energy efficiency.

These modifications are implemented with the objective of comparing different colors of the energy-saving film coating and examining the impact of double-glazed windows on energy efficiency. The research aims to provide insights into the most effective strategies for improving the building's energy performance. By analyzing the results, it seeks to identify the optimal combination of film coating colors and window types that can significantly enhance energy efficiency in the simulated building.

III. RESULTS AND DISCUSSION

To evaluate the energy use efficiency of various energy-efficient glazing systems, a dedicated supplementary film coating and double-glazing setup were integrated into the EnergyPlus model of the residential unit. The objective was to assess how these glazing systems influenced energy consumption. To attain this objective, we conducted an estimation of the annual energy consumption encompassing heating, cooling, and lighting for each distinct glazing system. Subsequently, we computed the annual energy consumption for heating, cooling, and lighting independently for every simulated glazing system and specific location. These discrete results were subsequently amalgamated to derive the total annual energy consumption. This rigorous analytical approach facilitated a holistic investigation into the overall energy utilization linked to diverse glazing systems.

By evaluating the total annual energy consumption, it was possible to determine the contributions of heating, cooling, and lighting to the overall energy usage for each glazing system, and it will also be included to identify the energy performance from power systems to building consumption and general equipment as influenced by other operating conditions and equipment variations, and develop processes to encourage the provider of efficient lighting and HVAC systems (heating with cooling loads), which will result in energy and cost savings [20]. This information provides insights into the effectiveness of different glazing systems in equipment of their effect on energy use. The real amount of energy used is reflected in the EDC invoice, with a comparison of the real monthly utilization of energy and the simulated consumption result that presented in Figure 2. The disparity between the actual and simulated rates of energy intensity for the year is relatively small, with 60.13 kWh/m^2 compared to 61.22 kWh/m^2, generally amounting to less than 1.78%. This indicates a high level of accuracy and reliability of the test's findings in capturing the power intensity within the building.

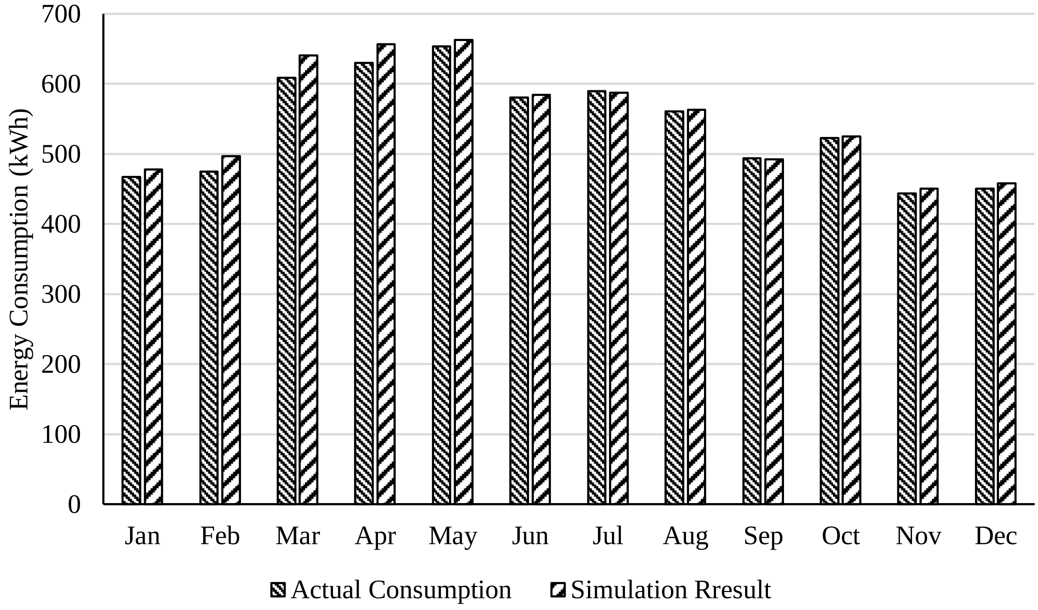


Figure 2. Monthly Energy Consumption and Simulation Study

3.1 Energy Performance of the additional film coating

The aimed of applying standard film coating insulation to a single-glazed window was to illustrate the potential energy-saving impact of a typical window improvement in residential buildings. The film coating serves as an additional measure aimed at bringing the single glazed windows in residential buildings up to modern standards. It is worth noting that while the film coating helps achieve this goal, there are other retrofit options with enhanced features that may be more preferable. Please find the results below:

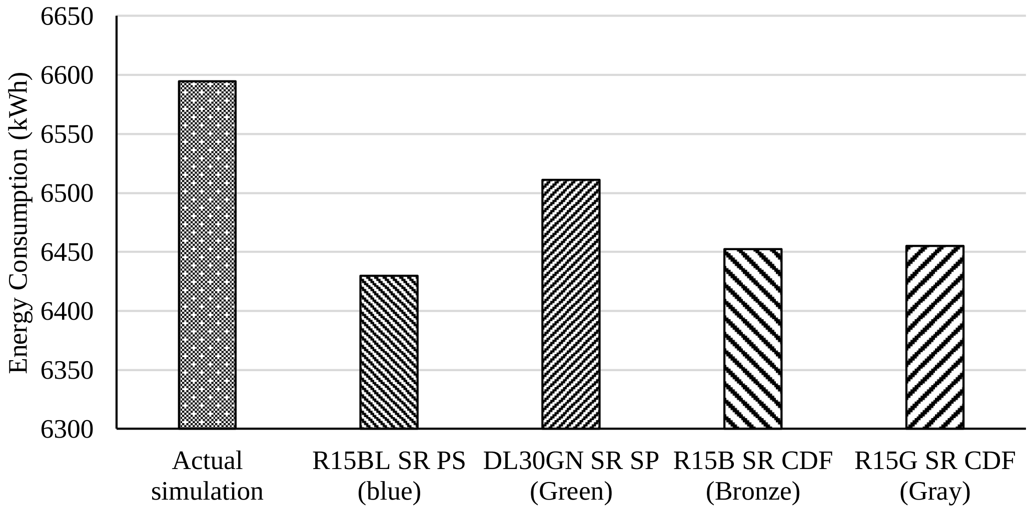


Figure 3. Actual energy consumption and glazed window with additional film coating

The addition of a high-level protection of the film coating to the existing glazed windows resulted in significant reductions in annual energy usage for the understudy residential building in this case studied. Specifically, the energy consumption of R15BL SR PS with blue color decreased by 2.50% (kWh), DL30GN SR SP with green color decreased by 1.30% (kWh), R15B SR CDF with bronze color decreased by 2.19% (kWh), and R15G SR CDF with gray color decreased by 2.17% (kWh). Figure 3 provides a visual comparison of real amount energy use before and after retrofit of the window, effectiveness with of adding the film coating to the glazing windows. Each pane of low-E (low emissivity) glass in the retrofit windows features a protective film coating that effectively reduces heat gain and visible transmittance while ensuring the window's quality is maintained. This model represents a significant advancement and will be the first to incorporate important improvements and effective technologies.

3.2 Energy Performance of the double-glazed window

The detached of evaluating the energy efficiency of standard double-glazed windows with aluminum frames was to determine the extent to which a simple window improvement can impact residential energy consumption. In Cambodia, double-glazed windows are not yet commonplace in newly constructed residential buildings. The inclusion of double-pane windows helps bring homes up to modern energy-saving standards, while other retrofit options will be considered based on an additional aesthetic study. For this particular case study, transparent glass without a film coating was used for the double-glazed window installation.

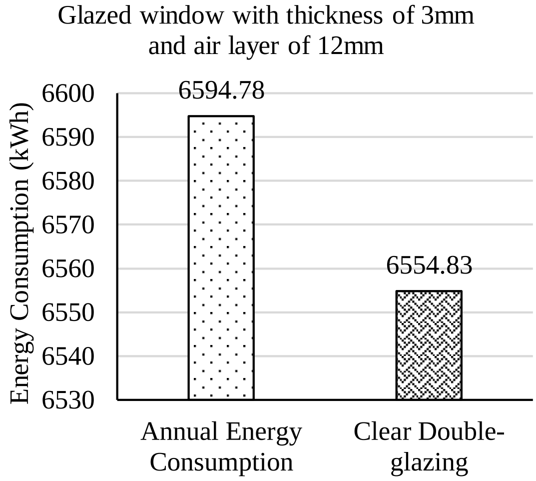


Figure 4. Comparison of the annual energy consumption of replacements with double-glazed window

Accounting to Figure 4 the result show that replacing transparency of double-panel windows with existing glazed windows led to a 0.61% decrease in the residential building's yearly energy usage, as observed with energy consumption simulation. Figure 5 showcases the monthly electricity demand within the study area, effectively highlighting the profound influence of varying glazed window types on the energy performance of the building.

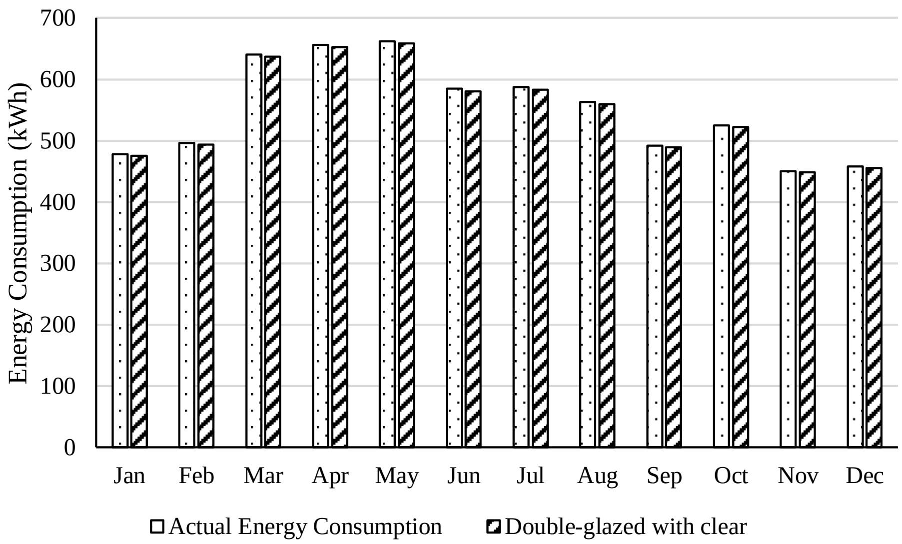


Figure 5. monthly comparison annual simulation with double-glazed window

3.3 Comparative Analysis of Glazed Window Performance

The simulation results clearly demonstrate a distinction between glazed windows without any additional coating and those with an applied film coating. The findings indicate that the utilization of film coatings on glazed windows has the potential to optimize the use of energy by minimizing heat transfer. The film coating's effectiveness is influenced by factors such as its color and the type of glass used.

The application of a film coating alters the internal thermal properties of the glass, resulting in a greater temperature differential between the center region and the edges of the glass [21]. This phenomenon accentuates the thermal properties of the glazed window and contributes to a rise in room temperature. Additionally, the addition of a film coating reduces solar absorptance and solar radiation, further enhancing the window's thermal performance. However, it is important to consider the impact of condensation when evaluating the energy-saving potential of glazed windows. In certain climates, the low protection of sunlight that is provided by single glazing is not as effective in achieving energy-saving goals when compared to non-coated single-pane glazing, once the heat exchange is not satisfied [22]. Therefore, a single-glazed window is optional and plays a significant role in heat transfer dynamics.

The simulation conducted in this study reveals an important finding: there is a threshold beyond which further improvements to windows may yield diminishing returns. While glazed windows with film coating are generally recognized as more efficient than single-pane windows with transparency, their impact on overall energy savings is highly contingent upon the specific characteristics of the building structure. In the case of a flat building, as exemplified in our current simulation, where the primary focus is on upgrading the windows, there is a limit to the potential savings achievable through window retrofits alone. The results obtained from retrofitting glazed windows with film coating indicate that this simulation represents an initial step towards reaching the maximum potential for energy savings. It is crucial to recognize that the effectiveness of window retrofits is effect of the various parameters, including all designation, orientation, and overall energy efficiency within the residential buildings. Other materials, such as insulation and HVAC systems, have renewable energy sources, was considered an influence on achieving substantial energy reductions. Thus, while glazed windows with film coating retrofit can yield considerable energy savings, it is essential to view them as part of a holistic approach to building energy efficiency. Further measures beyond window retrofits may be necessary to fully maximize energy savings in structures with more complex designs or higher energy demands. That all, this simulation provides valuable insights into the potential energy savings achievable through glazed window retrofitting. However, it emphasizes that reaching the savings threshold requires a comprehensive approach that considers the entire building system, taking into account various energy-saving measures and addressing the specific characteristics of the structure under study.

Table 4. Annual energy saving result with retrofit window (kWh)

Type of the simulation	cooling saving (%)	Total saving (%)
R15BL SR PS (Blue)	3.43	2.50
DL30GN SR SP (Green)	1.78	1.30
R15B SR CDF (Bronze)	3.03	2.19
R15G SR CDF (Gray)	2.97	2.17
Double-glazed with clear	1.40	0.61

Table 4.4 presents the annual simulation results for the single-glazed window with an additional R15BL SR PS (blue color) film coating. The energy consumption decreased from 6595 kWh to 6429.83 kWh, resulting in a reduction of 164.98 kWh.

At first glance, this may not appear to be a substantial decrease, equivalent to a modest savings of 2.50%, which amounts to approximately $29.37. The second highest savings achieved were 2.19%, equivalent to approximately $25.34 in total annual energy savings. These savings were achieved through the use of additional film coating and high-performance glazing.

Table 5. Utility Costs and savings for each type of simulation

Type of the simulation	Average monthly cost (USD)	Annual utility cost (USD)	Annual saving (USD)
Actual Simulation	97.82	1,173.87	-
R15BL SR PS (Blue)	95.38	1,144.51	29.37
DL30GN SR SP (Green)	96.58	1,159.01	14.86
R15B SR CDF (Bronze)	95.71	1,148.54	25.34
R15G SR CDF (Gray)	95.75	1,149.00	24.88
Double-glazed with clear	97.23	1,166.76	7.12

Table 4.5 provides a comprehensive overview of the utility costs and annual energy savings for each type of glazed window simulation. While the simulation results appear accurate, it is important to consider potential errors and other influencing factors, which will be discussed in a separate section. The energy models and simulations effectively demonstrate the efficiency of each glazed window type in reducing the overall energy consumption of the structure. These simulations serve as valuable tools for assessing the energy-saving potential of different window options.

The subsequent step involves analyzing the payback periods and conducting cost-benefit analyses for each simulation. This analysis will help determine the most suitable retrofit option for the building under consideration. Additionally, based on the prevailing Cambodian electricity rates per kWh, the utility expenditures for both the base scenario and each simulation can be calculated.

3.4 Analysis of Investment Cost for retrofitting glazed window

The calculation of utility costs for the residential building simulation and each simulation type is based on the Electricite du Cambodge (EDC) Electric Power rates per kilowatt-hour (kWh). As of January 1st, 2020, the EDC charges $0.178 (equivalent to 720 reils) per kWh for up to 201 kWh. To make an informed decision regarding the most suitable retrofit option for this building, a comprehensive cost-benefit analysis and payback period assessment will be conducted. This analysis will consider the financial implications and potential returns associated with each glazed window simulation type. By evaluating the cost-benefit ratio, considering factors such as energy savings and utility costs, it will be possible to determine which option offers the most favorable financial outcome. Additionally, term of payback with indicates the period needed to save sufficient energy to pay back the initial investment, will be taken into account. Considering the prevailing EDC electricity rates, these analyses will provide valuable insights into the economic viability of each simulation type and aid in selecting the optimal solution for retrofitting this specific building.

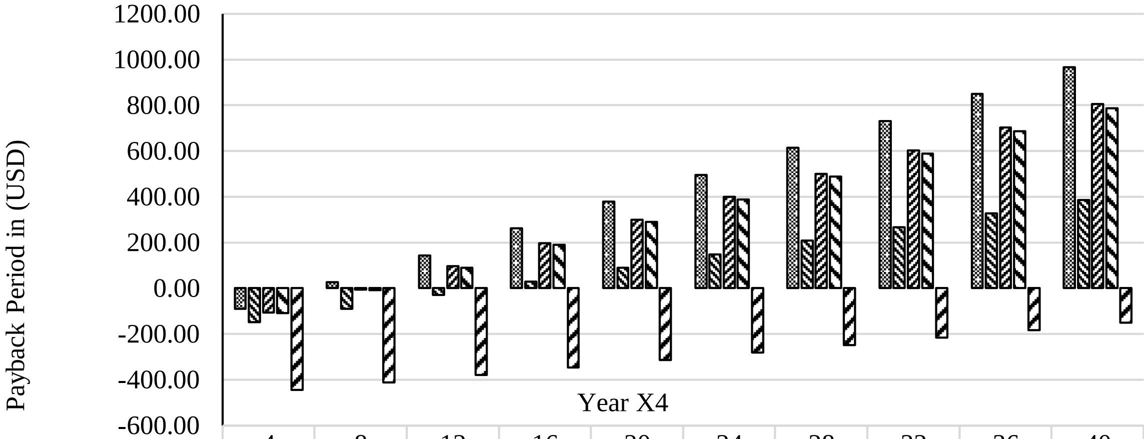
Table 6. The estimated cost of glazed window retrofitting

Glazed window simulation	Material cost ($\$/m^2$)	Total retrofit (USD)
Film coating	35	208.25
Double-glazed window	80	476

Table 6 provides an overview of the estimated costs associated with retrofitting the glazed window with an additional film coating and replacing single-pane windows with double-pane windows. The table presents comprehensive cost estimates for these retrofit options, which are crucial factors to consider when evaluating the feasibility and financial implications of the proposed upgrades. By examining the estimated costs provided, stakeholders can gain valuable insights into the investment required for implementing each retrofit option. These budget estimates are essential for evaluating the general economic sustainability of the suggested window improvements.

The payback period analysis reveals that homeowners who plan to occupy their property for an extended period, well beyond 7 years, can benefit from these window retrofits. Considering the lifespan of a residential building, 7 years is a relatively short timeframe. It requires time for the initial investment to be recouped, highlighting the importance of patience in realizing the long-term benefits.

After 24 years, the owner of the property can expect to receive over $10.6 in benefits specifically from the double-pane windows with transparency. Among the eight options considered, the additional film coating stands out as the most favorable choice. The simulation of single-glazed aluminum windows with the added film coating effectively demonstrates the energy efficiency improvements achievable by introducing modern standard windows to the building.



	4	8	12	16	20	24	28	32	36	40
R15BL SR PS (blue)	-90.78	26.68	144.15	261.61	379.08	496.54	614.01	731.48	848.94	966.41
DL30GN SR SP (Green)	-148.79	-89.33	-29.87	29.59	89.05	148.50	207.96	267.42	326.88	386.34
R15B SR CDF (Bronze)	-106.90	-5.56	95.79	197.13	298.48	399.83	501.17	602.52	703.86	805.21
R15G SR CDF (Gray)	-108.75	-9.25	90.26	189.76	289.26	388.76	488.26	587.77	687.27	786.77
Double-glazed with clear	-443.56	-411.12	-378.68	-346.24	-313.80	-281.36	-248.92	-216.48	-184.04	-151.60

Figure 6. The estimated payback period for each type of simulation is 40 years

While the additional film coating is more efficient than double-pane windows, the savings may not be as substantial, and the payback period could be longer. Aluminum, in particular, is not efficient in controlling heat transfer and is likely to result in temperature loss during certain months. Uncoated glass, especially in the afternoons of summer, may struggle to effectively block solar heat gain from the exterior walls. Therefore, investing a bit more to achieve better energy efficiency results appears to be a worthwhile consideration.

Out of all the options, the single-glazed window with an additional film coating emerges as the optimal choice. Film coatings offer a range of possibilities for residential buildings, catering to different specifications. They help limit heat absorption through the window frame, while Low-E coatings assist in reducing direct solar radiation gain inside the building. This solution proves to be both cost-effective and efficient, with a payback period of approximately 7 years.

IV. Conclusion

In this study, simulation software was employed to contrast the overall energy consumption among various types of glazed windows, including film coating and double-glazed windows. Specifically, the research examined the energy performance of retrofitting existing single-glazed windows with additional film coating on both sides. The study focused on a residential building in a townhouse style, situated in Phnom Penh city, with a total study area of 41.8 m^2, with the total façade of the glazed window set at 1.8% compared to the wall. By employing simulation software, the paper conducted an in-depth analysis to assess the energy consumption associated with each glazed window type. The aim was to provide a comparative evaluation of different options, considering the energy performance of film-coated windows and double-glazed windows in the context of retrofitting existing single-glazed windows.

The investigation conducted on simulated glazed windows successfully demonstrated the potential impact of window upgrades on existing buildings. Among the tested options, the additional film coating insulation emerged as the most cost-effective choice, with an estimated window cost and installation expense of approximately $208.25. On the other hand, double-glazed windows, with a cost of around $476, offered significant energy savings but were not compelling enough for the majority of simulated homeowners to prioritize window upgrades as their next investment. Considering the cost-effectiveness and energy efficiency improvements, the additional film coating insulation on existing single-glazed windows remains the preferred choice among the options evaluated. Film coatings offer a range of possibilities and specifications, making them suitable for residential structures. Moreover, they are relatively easy to apply, making it a viable do-it-yourself option for homeowners.

This paper examined a respected baseline of individuals considering window upgrades to enhance energy savings with a high-performance policy. However, the cost implications with potential benefits of different options, individuals can make informed decisions when window shopping and selecting the most suitable solution for their specific needs. the investigation of simulated glazed windows showcased the impact window upgrades can have on existing buildings. The additional film coating insulation on single-glazed windows stood out as the most favorable choice in terms of cost-effectiveness and energy efficiency. The results of this study provide valuable guidance for individuals aiming to improve the energy efficiency of their buildings while considering window upgrade possibilities. Furthermore, it is necessary to acknowledge that economic outcomes for individuals can differ significantly from those discussed in this research. Factors such as the variety of wall and roof types, climate variability, and occupant habits introduce complexities that go beyond the scope of this study, leading to diverse results in different cases.

V. Acknowledgment

We would like to extend our sincere gratitude to Thermal Lab for their invaluable support and provision of essential equipment, as well as to all the dedicated lab members for their remarkable contributions to this research study. Their assistance and involvement have been instrumental in the successful completion of this project.

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