Simulation-Based Life Cycle Assessment for Office Building Façade: A Case Study of the Leadenhall Building in London

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Abstract

High-rise glazing systems are among the most important components affecting energy efficiency. Through the lens of Life Cycle Assessment, glass has always been an unlikely material for large buildings due to its considerable energy consumption throughout the pre-use and post-use phases. Moreover, the use of high-tech materials has a negative impact on the environment. Therefore, the present study aims to assess a comparative life cycle of four different glazing system technologies (BIPV, smart glass, low-E, and double glazing) representing the most used commercial high potential glazing systems. The next step has been optimized for the Leadenhall iconic tower as the case study. In this analysis, energy simulation is combined with life cycle assessment to investigate the environmental impacts. ZEB-COM tool, Rhino®, and Grasshopper® have been used to calculate emissions, 3D modeling, and energy modeling, respectively. The results reveal that BIPV achieved 37% of total energy-saving and stood first. A hybrid solution (two glazing systems) has been proposed to eliminate negative aspects and increase livability. Although it can generate almost 30% less energy than the complete BIPV installation, with a specific design by the authors, it can cover aesthetic concerns in this system and compensates for 27% of the total energy demand of the Leadenhall project.

Keywords: *life cycle assessment, glazing system, comparative analysis, Leadenhall building, high-rise,*

1 Introduction

Climate change has become one of the most crucial global concerns (O'Neill et al., 2021). The construction industry is a big energy user with significant environmental consequences which are not negligible (Stegou-Sagia et al., 2007). Saving energy, particularly in buildings, is worthy of attention (Hee et al., 2015). In developed countries, residential and commercial building energy use accounts for 20–40% of total final energy consumption in the country (Pérez-Lombard et al., 2008). These energies are primarily utilized for residential space heating, cooling, and lighting for commercial buildings. In a building, the energy efficiency is influenced by its envelope, particularly its windows (Lee et al., 2013). Buelow-Huebe (2001) reported that a window is responsible for 20–40% of a building's lost energy. The minimum size of a building's window is required to restrict heat gain or loss (Buelow-Huebe, 2001).

On the other hand, a window enables natural light to enter a building. Furthermore, studies have proved the health benefits of natural sunlight and a view of the outdoors (Chang & Chen, 2005; Hee et al., 2015). The net energy gain from glazing and windows in buildings is determined by thermal and total solar energy transmittance. Therefore, picking optimal glazing systems or windows for a specific case regarding energy efficiency is challenging (Nielsen et al., 2001).

On the one hand, industrial development and increased housing and construction requirements led to skyscrapers' use (Ahmad et al., 2017). On the other hand, with global warming and the depletion of fossil fuels, interest in zero-energy buildings is increasing (Bravo-Hidalgo & Baez-Hernandez, 2019). In the next 20 years, the global market for zero-energy buildings is expected to overgrow, worth nearly $1.3 billion in 2035 (Cao et al., 2016). Advanced glazing systems have become an urgent requirement for high-rise office buildings to minimize energy consumption and adapt to external environmental conditions (He et al., 2019).

Using glazing technologies as building facades are becoming more popular (Rezaei et al., 2017). In a building, thermal comfort, light comfort, and skin health are all intimately tied to windows (Edlich et al., 2004). Furthermore, glazing systems provide acoustic comfort, vision, ventilation (Park & Kim, 2015), and photoprotection (Tuchinda et al., 2006).

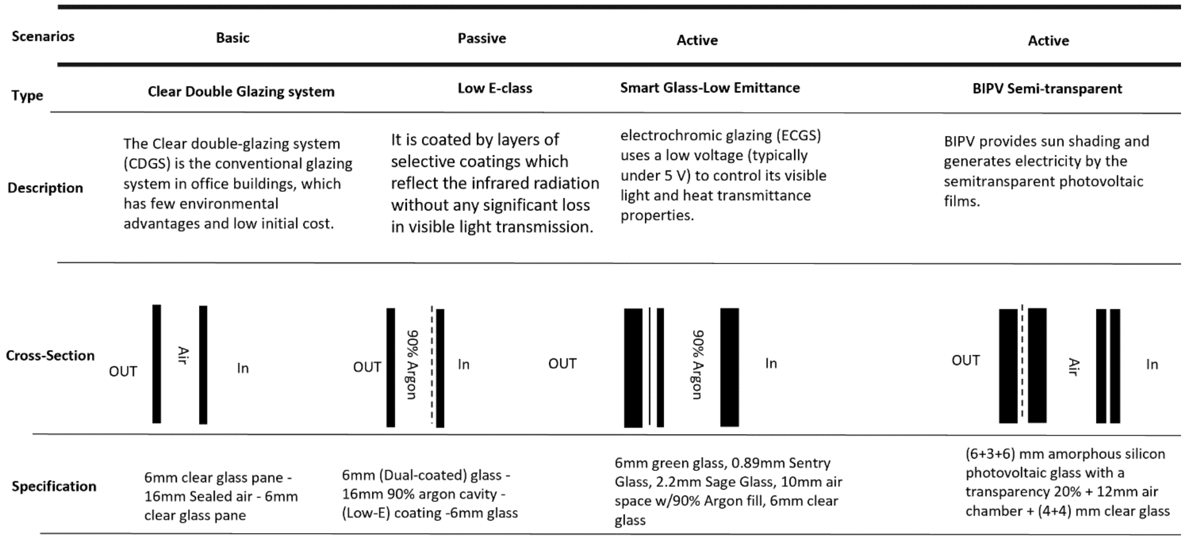

Figure 1: Specifications and descriptions for the alternatives

Because of these critical roles, windows must be designed and selected based on various factors, notably energy efficiency and visual comfort.
There are different approaches to classifying glazing systems. The glazing system, for example, can be classified into conventional glazing systems, advanced glazing materials and coatings, and smart (intelligent) technologies (Rezaei et al., 2017).

LCA is a widely used tool for comparing the environmental impacts of products or systems to assist decision-makers in selecting the most sustainable alternative (Elkhayat et al., 2020). Therefore, this study uses Life Cycle Assessment (LCA) methodology to investigate and compare the total environmental impacts of the four glazing systems in a commercial high-rise. For a sustainable building design, the starting point is a global "view" of the building's efficiency associated with all phases of a product's life cycle, including sourcing raw materials, processing these resources, producing, distributing, using, maintaining, and repairing the product, reselling or recycling them and disposal (Hernandez et al., 2019).
Through a comparative analysis, the present study aims to make a simulation-based life cycle assessment of four different glazing system technologies: conventional double glazing as the base case, passive Low-E glazing, Building-Integrated Photovoltaic (BIPV), and electrochromic smart glazing. These technologies are among the most worldwide used commercial high potential glazing systems. As the case study, these assessments are investigated for London's iconic commercial high-rise, the Leadenhall building. In this integrated approach, energy simulation is combined with life cycle assessment to investigate the environmental impacts.
The LCA results will determine which system has the lowest energy use and environmental impacts to support building designers and decision-makers in choosing the most environmentally friendly glazing system for their office buildings.

2 Methodology

The life cycle assessment methodology is generally broken down into four steps (Hernandez et al., 2019): goals and scope definition, Life Cycle Inventory (LCI) analysis, Life Cycle Impact Assessment (LCIA), and interpretation of the results. This comparative LCA analysis is accomplished according to the ISO14040:2006 guidelines and framework (2006a, 2006b), and (IEA) guidelines related to PV and BIPV, and the Norwegian Zero Emission Building (ZEB).

2.1 Goals and scope definitions

This comparative LCA study aims to find and contrast the environmental impacts of four different glazing systems to determine which glazing system's life cycle has the lowest energy use and environmental impacts for the case of a commercial high-rise in London. The Leadenhall building, known as Cheesegrater (Booth, 2014), launched in 2014, has 225 meters in height. As a result, it will aid in developing solutions to reduce the environmental impact of glazing systems. The life cycle impact data and analysis are supposed to assist architects and decision-makers in prioritizing the most environmentally friendly glazing system for high-rise office buildings.

The LCA evaluated the environmental impacts of the glazing system over its pre-use phase (manufacturing and construction) and use phase. ZEB Tool provided the LCI data associated with material extraction and manufacturing steps, and the Grasshopper® with Honeybee® plug-in calculated the BIPV energy produced and overall building's energy demand in the used-phase in Rhino®.

The scenarios are chosen by comparing the three major glazing system categories: passive, active, and BIPV, with a conventional double glazing system as the base case. Each class represents the most widely used commercial glazing technology for office building facades worldwide.

2.1.1 Functional unit

Defining a Functional Unit (FU) is crucial for developing and modeling a product system in Life Cycle Assessment (LCA). (Arzoumanidis et al. (2019) defined the functional unit as "a quantified description of the function of a product that serves as the reference basis for all calculations regarding impact assessment."

The present study considered the functional unit of the case study (the Leadenhall building) and four glazing systems alternatives (Fig. 1) as followings.

- ***Case study:*** the Leadenhall building in London. This 48-story building has 225 meters in height, 57,000 m² gross area, and a 75,000 m² façade area with a curtain wall glazing system. The service life of this project is considered 60-years with eight working hours per day (Young et al., 2013).
- ***Current façade*** (base case): double glazed clear insulating glass is assumed for the base case. The declared unit for processed glass is 1 m^2 of glass. Each 1 m^2 of double-pane insulating glass is 15.6 kg. The thickness of each pane is 3 mm (see Fig. 1).
- ***Alternative 1:*** passive Low-E coating. The declared unit for processed glass is one m^2 of glass. Each 1 m^2 pane weighs 7.5 kg, assuming a glass density of 2,500 kg/m3 and thickness of 3 mm. For a double unit, the specific weight is 15 kg (see Fig. 1).
- ***Alternative 2:*** electrochromic insulating glass unit. The declared unit for each with 1 m^2 of triple-pane glass is 17 kg. The thickness of each pane is provided in Fig. 3.
- ***Alternative 3:*** semi-transparent BIPV**.** The functional unit for LCA of BIPVs is 2 m^2 and 19 kg. Due to the lack of compiled data from the manufacturing companies, the U.S. Energy Information Administration (EIA) was used.

Furthermore, the degradation rate was assumed to be 0.7% per year**.** Transportation of all alternatives was considered 1000 km to the site (for example, Germany) by long trucks and 300 km for machinery on-site.

2.1.2 System boundaries

LCA's system boundary has been considered from cradle to site, and replacement contains the product stage and construction process stage, and use stage (A1-A5, B4, and B6). All alternatives are assumed to have the same production process as clear glass. Material extraction, manufacture, transportation, and on-site installation are part of the glazing system's pre-use phase. Only the operational processes were addressed during the usage phase. In this work, the service life of all alternatives is considered 60 years. Acidification, eutrophication, Global Warming Potential (GWP), Non-Renewable Energy (NRE), Ozone layer Depletion (OD), and terrestrial acidification and/or nitrification are the six impact categories studied because of their significance where (Elkhayat et al., 2020) define for each as the following.

2.1.3 Use-phase energy inputs

Grasshopper® plug-in is used to calculate BIPV's power generation. The simulations showed that the possible annual power generation is about 3,654 MWh/yr with a maximum efficiency of 19%. Alternatively, the energy generation in the building's use phase can be estimated by simple calculations. In the first step, finding approximate sunny hours in London is necessary. The monthly average daily sunny hours for five consecutive years were used to achieve this approximation. The average sunny hour is 4.4 hours per day. In calculations, 4 hours of sunlight per day is assumed. Considering 250 watt LG panel, each panel's nominal daily power generation can be calculated as 1 kWh/day (250 watts x 4.4 hours). Considering 75,000 m^2 usable façade area to install 2x1 meter panels, the annual possible power generation with 17% efficiency is about 2,556 MWh per year which is considerably lower than the results from the Grasshopper® simulation. In the LCA calculation, the power calculated by Grasshopper® has been employed. On the other hand, the Grasshopper-Honeybee® plug-in was utilized to estimate the average annual energy demand of the Leadenhall building.

2.1.4 Assumptions and limitations

The assumptions used in this comparative LCA analysis were chosen to simplify assessing environmental impacts and directly compare the three alternatives with the base case (clear double glazing system). The lifespan of buildings and transportation distances were considered to be constant. It is also assumed that all glazing systems are manufactured with the same process and location. As mentioned earlier, only the outer skin of the double façade was studied with the same framing in all alternatives. The dimensions of all glazing systems are considered the same. The materials with no effect on the LCA were not considered. Tab. 1 summarizes each of the scope definitions and assumptions.

Table 1: Summary of scope definition and assumptions

Functional unit	48-story (225 m) commercial high-rise in London with 57,000 m^2 heated floor, 75,000 m^2 façade area, and 60 years of service life.
System boundary	Pre-use and use stages of the life cycle and associated transportation, including A1-A5, B4, and B6 Environmental inputs: natural resources and energies Environmental outputs: emissions
Impact categories	Acidification, eutrophication, global warming potential, nonrenewable energy, ozone layer depletion, and terrestrial acidification/nitrification
Tools	ZEB Tool, Rhino®, Grasshopper® (Honeybee® and Ladybug® plug-ins)
Major assumptions	Assuming the same framing for all alternatives. Leadenhall building has a double-skin façade. Therefore, it was assumed that in all alternatives, the inner façade is the same, and only the glass of the outer façade is changing. The degradation rate was assumed to be 0.7% per year. BIPV panel dimension 2x1 meter with an efficiency of 17 %. Energy savings of Low-E and smart glass in the use phase were considered 5%, and 10%, respectively.
Distances/methods of transportation	1,000 km to the site for all glazing systems by long trucks. 300 km for machinery on-site.

Table 2: Sources of used EPD data

Alternatives	GWP ($kgCO_{2eq}/m^2$)	Sources
Double glazing	39.6	ASTM-EPD149
Low-E	13.7	ASTM-EPD149
Smart glass	7.43E+01	4787287780.101.1 Sage Glass
BIPV	2.79E+02	S-P-01817 Userhuus

2.2 Inventory Analysis

This inventory analysis phase analyzes and quantifies the environmental inputs and outputs associated with glazing system scenarios, considering the FU system limits and assumptions. The input energy, raw materials, output emissions, and solid waste for each stage of the life cycle of the scenario were analyzed. ZEB Tool's database was considered the primary source. ZEB Tool delivers extensive global and regional datasets that allow flow models to reflect integrated supply chains accurately and account for differences in the nation's glazing system.

2.2.1 Material inputs

The life cycle of glazing systems was assessed, starting with the extraction of raw materials (the "cradle"), followed by the use phase. Because float glass is the primary component of every Insulating Glass Unit (IGU), all glazing systems begin with the same production process. Then, specific manufacturing processes for each glazing system are used to create the IGU, mounted on a building façade at the end. Due to the comparative objective, the materials without effect on the LCA were not considered.

2.2.2 EPDs and Databases for LCI

The alternative EPDs listed in Tab. 2 were manually inserted into the ZEB Tool database. The functional unit and scope for all alternatives are 1 m^2 and A1-A3, respectively.

Figure 2: The Leadenhall Building (right photo: (Esper, 2007), and the left photo: (Howarth, 2014))

2.3 The case study

The Leadenhall Building (Fig. 2) is an iconic skyscraper in London that is 225 meters (738 ft) tall and 48 stories. It was launched in July 2014 and was designed by Rogers Stirk Harbour and Partners. Since this project's sightline is never in shadows, the morphology of Leadenhall could be a proper case study for this paper's purpose (Krolikowski et al., 2017). The general information about the building is elucidated in Tab. 3.

Table 3: The Leadenhall Building's overall information

Alternative name:	Cheesegrater
Location:	London, UK
Building function:	Office
Height:	225 *m* (48 stories)
Heated floor area:	57,000 m^2
Floors below ground:	4
Gross internal area:	84,424 m^2
Façade area	75,000 m^2

3 Results and discussion

In the present study, ZEB Tool is used to assess environmental impacts. Demand for lighting and equipment was set based on projected realistic use for a normalized operation period. The results show a correspondence between calculated and measured energy for the double-glazing, smart glass, and Low-E. However, BIPV performed differently by delivering 3,654 MWh/yr. However, there is considerable uncertainty in the estimated power generation. Furthermore, some factors have not been fully verified and may not be reliable for concrete conclusions. To optimize the energy use and delivered energy, several adjustments have already been made, such as:

- The BIPV market reports a variety of efficiencies between 5-19%. This study has chosen a relatively high-performance panel to get a more acceptable and feasible result.
- Considering the amount of energy saved during the operation of the ZEB Tool for Low-E and Smart Glass, this energy has been considered the on-site power production in the simulation.

Fig. 3 illustrates the comparison of GWP for each alternative, and by far, the highest belongs to BIPV with more than three times greater than others. At the same time, other alternatives with different specifications have almost identical impacts. However, there is a positive correlation between the technologies used in glazing systems and the total GWPs. Fig. 4 provides a phase-wise comparison of emissions in all the alternatives. Most other options' emissions come from A1-A3 (production) and B4 (replacement), and emissions in other phases are negligible.

Emissions related to material extraction and production, including related materials, are illustrated in Fig. 5. As seen, the CO_2 emission of the BIPV is significantly higher than other alternatives. Because BIPV has a higher specific weight and more components than other alternatives. The same information for the construction phase is provided in Fig. 6, indicating that the carbon emission of transportation in all alternatives is higher than installation in the construction phase. This emission showed a correlation with the weight of their materials.

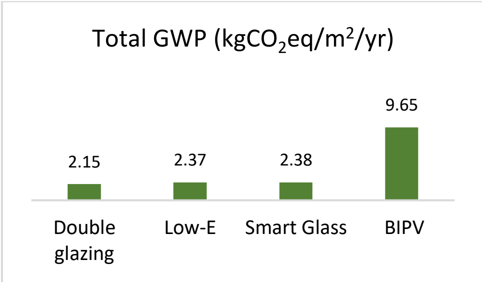

Figure 3: Total GWP for different alternatives

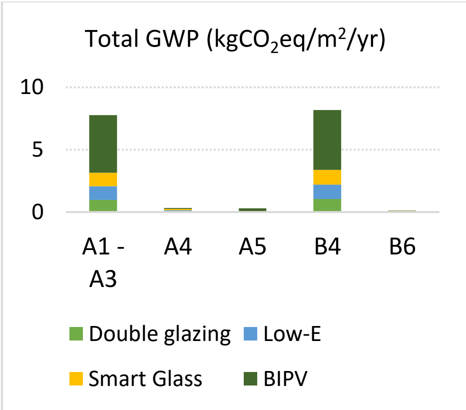

Figure 4: Total GWP per Step for all alternatives

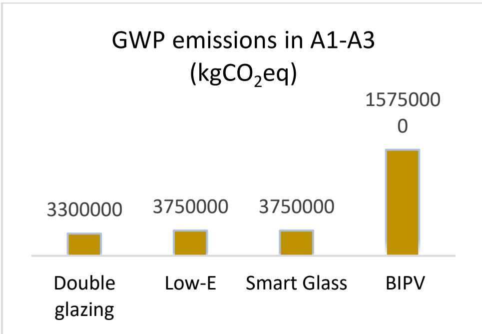

Figure 5: Production step's GWP CO_2e emissions

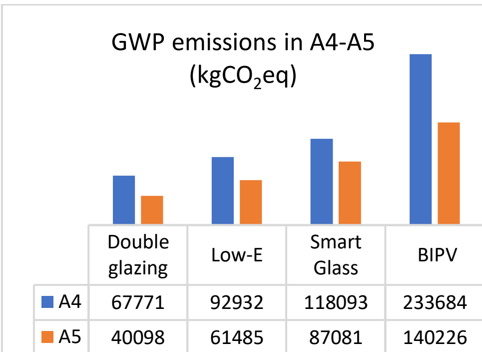

Figure 6: Construction step's GWP CO_2e emissions

3.1 Energy Demand

According to initial energy analyses in Grasshopper® with Honeybee® plug-in, the Leadenhall Energy Usage Intensity (EUI) calculated 62.5 Wh per square meter. The current building's average annual energy consumption is 9816000 (62.5 (Wh) x 8 (working hours) x 340 (working day)) kWh/yr for all different purposes such as lighting, cooling, heating, and electricity for electrical equipment. It is assumed that the total energy demand includes 18% for lighting, 18% for heating, 4 % for cooling, and 60% for electricity.

Using the Grasshopper-Ladybug® plug-in, the daily radiation (kWh/m^2/day) in a vertical surface (façade) has been calculated. As discussed, the Ladybug® plug-in result has shown that about 37,500 panels can provide 37.2% of the building's annual energy. It should be noted that each panel's surface area modeled in Rhino® is 2 square meters (2x1 panels).

As presented in Fig. 7, in a building with smart glass (electrochromic), the energy demand is the lowest because it allows occupants to beneficiate from natural light without suffering from glare or heat. In contrast, BIPV consumes the highest energy due to less radiance and natural light, forcing occupants to have more lighting and heating energy. On the other hand, Low-E positively affects energy demand compared to fully transparent double glazing systems. As discussed earlier, only BIPV has this advantage in energy production and produces a considerable amount of energy (37% of its energy demand) on site. The negative values for smart glass and Low-E represent the energy saving effect in the building. Smart glazing technology performs more efficiently than other alternatives.

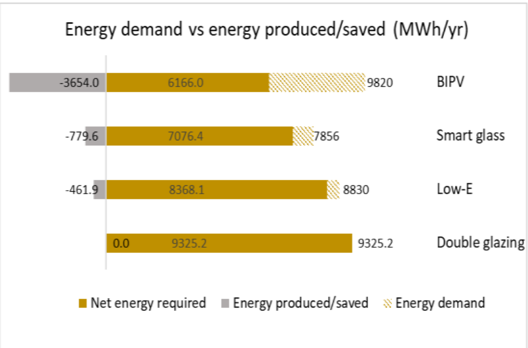

Figure 7: Leadenhall building's comparison of energy demand and production/saving in different alternatives

Fig. 7 proves that a conventional glazing system needs the highest energy compared to other alternatives. Because not only does it have the second-highest energy demand, but also it has no savings or energy production. BIPV shows the best performance in total energy demand due to its significant electric energy generation, and the building's net energy for one year of operation is the lowest.

More detail, the proportion of electricity from the building's energy demand in all alternatives is the highest (more than 50% of their total demand). Because the electrical consumption of the equipment is independent of the glazing type, BIPV passes the lowest sunlight among all alternatives. Therefore, as one of the main disadvantages, this scenario needs considerably higher energy demand for lighting. While in other scenarios, there is a minor deviation. According to the result, around 40% saving in the annual energy demand of the Leadenhall building can be achieved. Moreover, due to a lower U-value than a regular glazing system, the BIPV leads to substantial energy savings and reduced pollutant sources (Olivieri et al., 2014). However, other negative aspects include a lack of aesthetic added value, radiation loss, and a darker view.

Therefore, in the continuation of this study, the LCA of the proposed scenario (hybrid scenario) using a multi-parameter optimization process to decrease the negative aspects of BIPV from an architectural point of view is studied.

3.2 Hybrid Scenario

There is a possibility to optimize the BIPV façade and reduce the disadvantages. Some BIPVs were replaced by clear double glazing in the proposed hybrid scenario. As seen in Fig. 8, dividing each floor's glazing into three sections, the middle section of the BIPV scenario can be replaced by a clear double glazing window. Therefore, the view at eye level is preserved in the hybrid scenario. In most office spaces, desks mostly block the lower section, which causes a minor problem for people. This LCA and energy demand approach shows almost 30 % less carbon emission in the product and use stage. It also produced 70% of the energy, generating full BIPV glazing. Fig. 9 compares the GWP of the hybrid scenario with other alternatives.

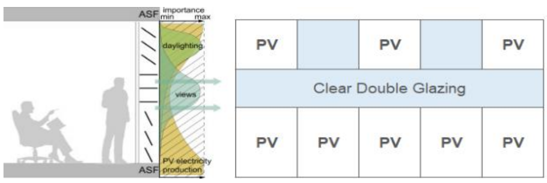

Figure 8: left: the conceptual cross-section of BIPV and clear glazing glass in eye-line borrowed from (Nagy et al., 2016) , and right: suggested hybrid scenario configuration arrangement.

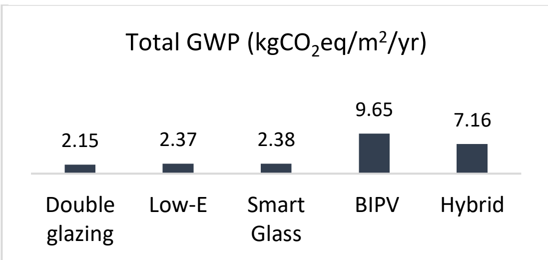

Figure 9: Total GWP for different alternatives

4 Conclusion

The present study investigates the LCA of four scenarios representing the most widely used commercial high-potential glazing systems. The conventional double glazing system showed the lowest GWP in the LCA study. The energy analysis was carried out to understand how these glazing systems' energy savings in the use phase could offset the initial energy consumption in the pre-use step for raw materials extraction, transportation, production, and installation. Due to the generated electricity, the BIPV achieved a 37% saving in required total energy, which puts it first as the most energy-saving system. A hybrid glass construction system has been proposed due to some negative aspects of using BIPVs from an architectural point of view. Although it can generate 30% less energy than the full BIPV scenario, it covers aesthetic concerns in this system and compensates for 27% of the total energy demand of the project. However, Low-E and smart glass consumed more energy in the pre-use phase than the conventional glazing system; their energy savings in the use phase (5%, 10%) could offset these initial consumptions to achieve lower total energy consumption values. This study had limitations due to the lack of technical data from suppliers and software databases. As a future study, it is suggested that applying different climates, considering economic aspects, extending boundaries, and assessing the environmental impacts under uncertainty would be appropriate starting points.

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