Embodied Energy Analysis of Vacuum Insulated Glass: A Hybrid Life Cycle Assessment Approach

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Abstract

This study looks at the embodied energy use and greenhouse gas (GHG) emissions in the Vacuum Insulated Glass (VIG) supply chain using a Hybrid Life Cycle Analysis (hLCA) approach. VIG technology provides much better insulation performance compared to traditional Insulating Glass Units (IGU), but we need to understand its complete environmental impact by looking at both operational benefits and embodied energy costs. Our findings show that VIG manufacturing has roughly 5 times higher embodied energy and about 1.3 times higher GHG emissions compared to IGU manufacturing, per square meter. However, the operational energy savings of VIG can make up for these higher initial environmental costs. The study shows that electricity use, and gas supply are the main contributors to GHG emissions in VIG production, with natural gas extraction and hard coal sectors having the biggest embodied energy impacts.

Keywords

Life Cycle Analysis, Input-Output Analysis, Vacuum Insulated Glass, Manufacturing

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1. Introduction

In 2021 it was reported that the building sector consumed 132 exajoules (EJ) of energy—that's about 30% of global final energy use. Of this energy, 34%, or roughly 10% of total global energy use, was due to the electricity sector. This high impact of electricity use in buildings is the result of the high demand of heating, cooling, and appliance use, especially in OECD countries. This leads to about 6 $GtCO_2$ in indirect greenhouse gas (GHG) emissions (IEA 2022).

Even though efforts grow to add more renewable energy, the building sector's emissions have still grown by 0.5% annually since 2010. This is driven by population growth, more appliance use, and increasing extreme temperatures. In OECD nations, over 30% of building energy demand comes from space cooling and heating, with cooling expected to match or even surpass all other growth sectors, including electric vehicles (IEA 2022). Within the existing building stock in developed nations, heating demands have increased by 10% since 2010. This is due to poor insulation and inefficient building envelopes, with windows specifically contributing up to 60% of energy loss because of high heat transfer through the glass and frames.

Improving the insulation level of building envelopes can reduce heating and cooling needs—this is actually the sector's greatest potential for cost-effective GHG reductions through energy-efficient technologies. For example, energy-efficient windows can lower emissions during a building's operational phase, which includes heating, cooling, lighting, and appliance use. Studies have shown that maintaining or replacing windows significantly improves energy savings, with optimal designs identified for different climates (Tsikaloudaki et al, 2012).

However, while improving efficiency often reduces operational emissions, it can increase embodied energy—the total energy required to extract, process, manufacture, and transport materials—and lifecycle CO_2 emissions, particularly for building materials with high embodied carbon. Embodied carbon covers emissions from raw material extraction all the way to disposal. The Life Cycle Analysis (LCA) technique allows us to precisely determine the environmental impacts associated with a product or service, such as energy use, resource depletion, and/or GHG emissions (ISO 1997, Hellweg & Milà 2014).

Previous studies have shown that buildings using low-energy designs often show a 25% increase in embodied GHG emissions despite achieving operating energy savings of 50%. The embodied share of a life cycle analysis varies significantly with geography, climate, raw materials, and production methods, which really affects the payback periods of products.

As mentioned, windows are a major source of uncontrolled energy loss. Using insulated window technologies is essential for improving building operational energy efficiency. In recent years, Vacuum Insulated Glass (VIG) has emerged as an alternative to traditional Insulating Glass Units (IGU), offering superior insulation performance. While the VIG technology reduces operational energy use, it's also critical to assess the embodied energy and emissions associated with its manufacture and supply chain, to understand and quantify the environmental impact of the product.

The goal of this paper is to characterize the embodied energy use and GHG emissions within the VIG supply chain using a Hybrid Life Cycle Analysis (hLCA) approach, based on Input-Output tables, and compare it to the traditional IGU product.

2. Vacuum Insulated Glass

There is considerable potential to reduce the environmental impact of indoor climate control by using highly insulating windows in buildings. Globally, in cold climates, using double-glazed IGU windows is commonplace. An IGU window in its simplest form consists of two panes of glass held apart at an optimum distance of 12–18 mm in a rigid frame, with the gap between the panes filled with air. Further increases to the insulating properties is possible by increasing the distance between the panes, the number of panes (and thus number of gas gaps), by using low emittance coatings, or by filling with lower thermal conductivity gases such as Argon, Krypton, or Xenon. The air-to-air conductance of a single pane of glass is about 6 W m^{-2} K^{-1}; a double-glazed IGU is about 3 W m^{-2} K^{-1}; a double-glazed IGU constructed using low emittance coatings and Argon gas is about 1.8 W m^{-2} K^{-1}, and a further reduction in conductance is achieved to about 0.7 W m^{-2} K^{-1} using a triple-glazed IGU window with low emittance coatings and Argon gas (Collins et al, 1995, Simko et al, 1998).

The VIG is a thin, lightweight, and highly thermally insulating technology with high visible transmittance. The concept of VIG originates from Dewar's work, who made vacuum insulated double-layered flasks to collect and maintain a low temperature liquid. The concept of an equivalent flat panel vacuum insulated device was first reported in the patent literature by Zoller in 1913 (Zoller 1924). Since then, different academic and commercial groups have shown strong interest in building a commercially viable VIG product to be used in fridges and buildings.

The origin of the invention for the first commercial VIG product is attributed to the work reported by Robinson and Collins, from the University of Sydney, in 1989. Their invention used a continuous solder glass (also known as glass frit) edge seal to bond the glass panes together as the hermetic seal to maintain the vacuum between the panes. This breakthrough was significant since previous attempts—for example using laser melting to fuse the panes at their edges—proved unreliable and costly (Collins et al, 1995, Simko et al, 1998).

The basic construction of a VIG window consists of two panes of glass separated by an evacuated gap about a tenth of a millimeter wide. In the gap, an array of disk-shaped spacers (commonly known as pillars) is placed to maintain the separation between the glass panes under the action of atmospheric pressure. By evacuating the gap, the contributions of gaseous and convective thermal transfer to the overall thermal conductance of the window are reduced to a negligible amount, and the overall thermal conductance depends on the surface-to-surface radiative transfer (limited by using low emissivity coatings) and the contributions due to the pillars.

Since the vacuum gap is thin, there is the advantage of an overall window thickness that is much less than traditional IGU products; using 3 mm thick glass panes, the overall thickness of the VIG would be about 6.2 mm. The first commercially available VIG product was successfully licensed by the Collins group at the University of Sydney and produced by NSG Japan; this resulted in a 1 m^2 VIG with an air-to-air thermal conductance as low as 0.6 W m^{-2} K^{-1}. Different approaches by other groups to the design and manufacture have led to several VIG products, some able to deliver an air-to-air centre-of-glass thermal conductance as low as 0.35 W m^{-2} K^{-1} (Collins et al, 1995, Simko et al, 1998, Kocer et al, 2023).

3. Life Cycle Analysis of a Window

Buildings are complex structures constructed from many different components. Windows, being one of the most important elements, typically contribute 10–25% of a building envelope area. Because of their transparent nature, windows make up one of the most prominent elements of the building envelope and energy impact. Efficient window glazing and frame designs are crucial and contribute significantly to overall performance, so they must be considered in the final 'energy use' associated with heating and cooling.

Despite the reported efficient performance of windows, particularly thermally insulating products, during the operational phase, there are significant upstream impacts associated with the selection of materials in sourcing, manufacturing, and delivering the product. Material impact in the case of windows is comparatively high compared to other building materials, which results in excessive impact when compared by their mass and unit area. On this basis, a complete Life Cycle Analysis (LCA) can act as an effective tool that can inform building designers and contractors to choose windows that are high-performance yet have minimum environmental impact (Asdrubali et al, 2021).

Several studies have been published for different types of windows and frames using the well-established LCA methodology to quantify environmental impacts from cradle to grave. The literature concerning window LCAs are mostly categorized into single elements of the window, with the greatest number of publications about window frames. This is followed by fewer publications concerning the glass and shading. However, there are several publications that report complete window system investigations.

Even though most works focus on operational performance, Litti and Weir & Muneer (Litti et al, 2018, Weir & Muneer 1998) carried out the first LCA that considered embodied energy impacts of an IGU window system. They obtained data for the study from detailed audits of manufacturing processes of a factory based in Norway. Their study concluded that using Xenon and Krypton gas significantly changed the embodied impacts of the windows, where Argon gas resulted the lower embodied impact compared to the other components.

The conventional process based LCA modelling (PLCA) methodology suffers from a 'truncation error' because of methodological boundaries. Process-based LCA uses a bottom-up technique where processes from cradle to grave can be assessed thoroughly using case-specific data, which includes resource requirements, associated emissions, supplier contributions, use, and end phase impacts. However, the system boundary for PLCA is defined based on the understanding that consecutive upstream production stages have minimal effect on the complete inventory. This means that only the lower orders of upstream requirements are considered, resulting in a reduction of the assessment scope and higher contributions to truncation uncertainty (Lenzen 2000, Yu & Wiedmann 2018).

An alternative to PLCA is the Input-Output analysis (IOA) methodology, which was developed by Leontief. IOA is a top-down economic technique where national input-output tables, which represent materials and processing interrelationships within various industries of an economy, are adopted. The downside of IOA is that, as the entire economy is covered, the economy is in an aggregated form. Of the two methods, PLCA is more specific and precise; however, IOA is more complete and easier to perform, with much less data needed, and is less labour intensive. To analyse complex supply chains, selecting a complete system boundary has become one of the fundamental tasks within life cycle assessment. This has contributed to the development of the analysis technique known as hybrid-LCA (hLCA), which embraces the strengths of both IOA and PLCA. Combining both approaches results in more specificity, as bottom-up process data is included (avoiding the aggregation error), and system completeness is delivered since the truncation error is eliminated. This technique has gained wide recognition around the world for assessing triple bottom line impacts and carbon foot-printing of a product or technology. Furthermore, it has been shown to provide detailed insights in manufacturing (Lenzen 2002, Suh et al, 2004, Stephen et al, 2013).

Although individual components of buildings have been studied by various research groups, including window systems, an hLCA publication focusing on thermally insulating window systems has not been found. This study, for the first time, undertakes an environmental assessment of traditional IGU and VIG window products, using input-output data and engineering process data to employ the hLCA methodology (Stephan & Stephan 2014, ISA 2019).

It is important to acknowledge that precisely defining the production processes and exact raw materials used in commercial VIG and IGU manufacturing presents significant challenges, as this information is often proprietary and varies between manufacturers. For this analysis, we have defined a product and manufacturing process that represents a reasonable estimate of typical VIG production, with a parallel approach undertaken for the double pane IGU to provide a meaningful comparison baseline. This methodology allows us to establish a comparative perspective on environmental impacts while maintaining the integrity of the analysis, despite considerable information constraints.

This approach offers valuable insights into the relative sustainability merits of both technologies, and insight into potential changes that could further reduce negative impacts. Moreover, this work will encourage future studies based on more specific production data which should become available through industry collaborations.

4. Implementing the hLCA Methodology

4.1. The hLCA Assessment

The hLCA approach is used to determine the embodied energy and GHG emissions of the VIG and IGU products. The hLCA was carried out using both bottom-up engineering process data and top-down input-output data identified in the data sources. The LCA framework used for the study is based on the International Organization for Standardization (ISO) 14040 standard for life cycle assessment (ISO 1997).

Getting detailed material and manufacturing data of IGU and VIG products is difficult because this information is commercially sensitive. In this work, data on the manufacturing process of VIG was compiled based on previous research work undertaken at the University of Sydney, in the prototyping of VIG units and commercial interactions. Data concerning IGU production was obtained from public literature and various interactions with commercial manufacturers.

The data was synthesized for the scope of this study, the manufacturing limits were, for VIG production Annealed glass thickness 4mm, Area of one unit of VIG 0.62 m^2, Annual production 356,000 units/year, Annual production 220,696 m². And for IGU production, Annealed glass thickness 4mm, Area of one unit of VIG 0.62 m^2, Annual production 479,104 units/year, Annual production 296,883 m². The expenditure categories were identified as given in Tables 1 and 2, for VIG and IGU, respectively. The economic multi-region input-output (MRIO) table for the study was obtained from the Global Resource Input Output Assessment (GLORIA) database for the year 2019 (Yang et al, 2017).

The initial step of a life cycle assessment is to define the goal and scope of the study. The goal of this study is to calculate the embodied energy of VIG and IGU for a sustainability comparison study. Furthermore, to complement the study, calculations on GHG emissions during the production of both types of windows are carried out. The study is extended to identify the energy return on investment by using existing literature on operational expenses for the two types of window systems. The expenditure for the production categories is calculated based on the functional unit of 1m² of window glazing. Therefore, the results obtained will correspond to the energy use and GHG emissions for the 1m² production of the VIG and IGU products (Leontief 1996).

Since the study adopts an hLCA methodology, the entire global economy is chosen as the system boundary, which includes the upstream supplier chain transactions. This enables the study to be more complete; however, the data presented in the MRIO tables are in an aggregated form. In addition, for the process analysis, unit processes from the extraction of raw materials to the manufacturing processes are included.

4.2. Inventory analysis

The original VIG invention uses solder glass material as the edge seal and is manufactured using a batch process. Globally, many commercial VIG producers employ the edge seal material and the batch process.

The generic steps in VIG batch manufacturing are as follows:

- Cut, drill, and prepare the required glass panes, with an access point for evacuation,
- Dispense or screen print edge seal material on one, or both, glass pane(s),
- Place pillars on the bottom glass pane, and pair the two glass panes,
- Place the unit in a furnace, heat to remelt edge seal material, and form the hermetic edge seal,
- After the unit is cooled, attach a vacuum pump and evacuate the internal gap until base pressure is reached,
- Tip-off (i.e., seal permanently) the evacuation access point, to seal the VIG unit.

This generic process is commonly known as the batch furnace process. The term 'batch' is used to highlight the fact that multiple units can be sealed in the furnace and subsequently evacuated simultaneously. Specifically, this process is known as the two-setup process since the edge sealing and the evacuation of the gap are performed as two independent steps. This is the original production technique developed at the University of Sydney. Today, many of the commercial manufacturers use a single-step batch process, which means that the unit is sealed in the furnace and before the unit is cooled to room temperature, the unit is evacuated and sealed. There are several advantages in this single step process, nevertheless, the difference in the manufacturing process does not significantly impact the hLCA process and outcomes. In this work we have assumed that the VIG is produced using the batch process, and the edge seal is of solder glass.

The IGU manufacturing process is well known, and has had decades of significant engineering progress, which has led to well defined 'off-the-shelf' production equipment arrangement that several engineering companies offer as a package for potential producers. There are differences in the manufacturing steps, however, the basics steps are,

- Cut and prepare the required glass panes, with any surface features added as needed,
- Prepare the edge spacer, which includes the addition of desiccant material into the spacer,
- Place the spacer onto the glass pane, and pair the two glass panes,
- Dispense edge seal material on the edge of the panes to seal in the spacer,
- Inject the required low conductivity gas into the gap between the glass panes,
- Apply further processing of the edge for quality control.

The Life Cycle Inventory (LCI) is compiled to quantify the embodied energy and emissions during the manufacturing process of the VIG and IGU manufacturing steps. Starting from the extraction of raw materials to the completion of the product at the factory. The simplest classification terms for this process, is that all aspects of the manufacturing where there is external expenditure is to be captured in the LCI. For example, purchasing and operating the processing equipment will be included. However, the cost of equipment maintenance performed by staff employed at the production facility is not, since it is captured in the overall labour contributions included in other steps of the hLCA.

The data used for the study were acquired for the USA region. The expenditure categories and values for both VIG and IGU are derived based on the production limits and the expenditure categories and contributions are provided in Table 1, where the breakdown of the more complex categories provided in Table 2 and Table 3.

Table 1: VIG & IGU Expenditure Categories and Contributions, [per m^2].

Category	VIG Production	IGU Production	Difference IGU to VIG	Absolute Difference
Building & Grounds	$1.2	$1.2	0%	$0.0
Office & Admin Equipment	$0.3	$0.3	0%	$0.0
Admin & Overhead	$0.9	$0.9	0%	$0.0
Raw materials	$9.1	$9.5	-4%	-$0.3
Assembly Line Equipment	$3.9	$1.3	189%	$2.5
Initial glass storage and handling	$0.3	$0.3	0%	$0.0
Cleaning & Inspection Equipment	$0.4	$0.4	22%	$0.1
Energy Use (Electricity use in Production)	$13.5	$1.9	603%	$11.6
Packaging & Logistics	$1.8	$1.5	21%	$0.3
Maintenance (Production)	$0.2	$0.1	180%	$0.1
TOTAL COST	$31.6	$17.3	82%	$14.3

Table 2: A breakdown of more complex categories with multiple inputs (equipment) [per m^2].

Assembly Line Equipment	VIG Production	IGU Production
Miscellaneous equipment	$0.09	$0.09
Glass cutting	$0.27	$0.27
Edge treating equipment	$0.34	$0.34
Assembly equip of edge spacers and glass panes	--	$0.64
Placement equip of pillars	$0.28	--
Solder glass mixing equipment	$0.16	--
Dispensing robot of solder glass	$0.02	--
Drying furnace for solder glass	$0.40	--
Baking furnace of solder glass	$1.20	--
Evacuation system	$0.60	--
Tube seal metal cups	$0.03	--
Getter activation equipment	$0.20	--
Getter Installation Equipment	$0.04	--
Glass pairing equipment	$0.20	--
Glass drilling	$0.03	--
SUB-TOTAL	$3.87	$1.34

Table 3: A breakdown of more complex categories with multiple inputs (materials) [per m^2].

Raw Materials	VIG Production	IGU Production
Glass Materials	\$5.43	\$5.43
Solder glass/sealant-spacers	\$2.10	\$2.09
Pillars	\$1.30	
Desiccant / getter	\$0.30	\$1.90
Argon		\$0.05
SUB-TOTAL	\$9.13	\$9.47

4.3. Calculation Steps; The Input-Output analysis

The direct and total (direct and indirect) intensities were calculated using the input-output framework introduced by Leontief (Leontief 1996). First, total output of the global economy was calculated using the equations:

$$x = Ax + y \quad (1)$$

$$x = (I-A)^{-1} y \quad (2)$$

where:

- x = (19680 x 1), is the total output of the economy, regions;
- A = (19680 x 19680), direct requirements matrix;
- y = (19680 x 1), final demand matrix, sectors;
- I = (19680 x 19680), identity matrix.

The physical quantities such as energy and GHG emissions were added to the input-output tables as satellite accounts using the equations:

$$m = qL \quad (3)$$

$$L = (I-A)^{-1} \quad (4)$$

$$q = Qx^{-1} \quad (5)$$

where:

- L = (19680 x 19680), Leontief inverse, or total requirements matrix
- q = (1 x 19680), direct intensities
- m = (1 x 19680), total intensities
- Q = energy and GHG data
- x^{-1} = the inverse of the diagonalized total output vector

The total impacts from the upstream layers can be broken down into individual sectors from each layer by modifying the basic IO equation as:

$$Q = q\#Ly^* = q(I-A)^{-1}y^* = q\#y^* + q\#Ay^* + q\#A^2y^* + q\#A^3y^* + q\#A^ny^* \quad (6)$$

Where:

- # denotes elementwise multiplication
- $q\#y^*$ = onsite impacts for the VIG manufacturing, layer 1,
- $q\#Ay^*$ = immediate impacts from the upstream suppliers, layer 2,
- $q\#A^2y^*$ = impacts from the suppliers' suppliers, layer 3, and so on, until the n^{th} layer,
- y^* = final demand vector

5. Discussion of Results

The results of the hLCA calculations were analysed based on the data inventory and impact categories. The contribution of embodied energy and GHG emissions from the manufacturing process of VIG and IGU product at a 1m² window size are presented in Table 4. The total impacts of embodied energy for VIG are found to be 5 times higher than that of IGU. Similarly, GHG emissions are higher for VIG; however, the difference is only approximately 2.3 times higher than that of IGU.

The direct impacts—impacts that occur directly during the manufacturing process itself—of GHG emissions for both window types are higher in percentage with respect to the embodied energy impacts. As such, the direct GHG impacts account for over 77% and 86% for VIG and IGU, respectively. On the other hand, the direct impact of embodied energy is significantly lower compared to the total impacts for both window types, attributing only 18% and 13% for VIG and IGU, respectively.

Table 4: Energy and GHG contributions, direct and total, for VIG and IGU manufacturing.

	VIG		*IGU*	
	Direct impacts	Total impacts	Direct impacts	Total impacts
Embodied Energy (MJ/m^2)	96.28	524.07	13.69	106.39
GHG (in kg of CO_2 eq./m^2)	84.51	106.59	41.14	48.00

To narrow down the impacts of interest and to identify the categories and regions responsible for the highest allocations, the impacts were disaggregated according to industry sectors and regions. The final calculation results in Table 4 were obtained using the window glazing industry data for the USA where the bottom-up process data were collated with the GLORIA database and MRIO table. Since the data from the expenditure categories were augmented within the USA region, almost all the GHG emissions are attributed to the USA region for both VIG and IGU. It is found that the remainder of the emissions are less than 5% of the overall emissions for both VIG and IGU for all other regions.

Moreover, the energy allocation for each region exhibits a similar result to the GHG emissions, as the majority of the embodied energy is attributed to the USA for both VIG and IGU. However, it's notable that, unlike the marginal GHG emissions, energy usage accounts for at least 39% of the total embodied energy over the regions other than the USA for the VIG and IGU. This indicates that energy use, or allocation within upstream activities, is substantially higher compared to GHG emissions in both VIG and IGU manufacturing.

Examining the regions with the most significant impacts enables us to identify which regions experience the highest impacts across the entire supply chain in the upstream activities. Pinpointing the sectors with the highest impacts allows the implementation of initiatives for alternative efficient processes within those supply chains.

The highest greenhouse gas (GHG) emissions for VIG are primarily associated with the 'Other ceramics' sector, which is grouped within the broader category of 'Other manufacturing' and accounts for 46% of total emissions. The second and third largest contributors are the electricity supply and gas supply sectors, comprising 34.2% and 14.6% of total emissions, respectively. Given that there was no direct expenditure on the gas supply sector, this represents a supply chain impact originating upstream from the point of production of VIG.

The high GHG emissions contribution from electricity can be attributed to the reliance in the USA on natural gas, which contributed to 38-40% of its electricity generation in 2021. While natural gas is a cleaner alternative to coal, it still releases substantial greenhouse gases during combustion. Additionally, sectors such as gas supply indirectly contribute to the total GHG emission results through upstream activities associated with extraction, processing, and transportation, increasing the total emissions attributed to the sector.

A similar emission pattern is observed across the IGU, albeit with lower magnitudes across the sectors. The highest greenhouse gas (GHG) emissions in IGU manufacturing are attributed to the 'Other manufacturing' sector, which accounts for 75.1% of total emissions. This finding aligns with the substantial carbon footprint associated with the use of annealed float glass in IGU production. The electricity sector represents the second largest contributor, accounting for 12.3% of the total emissions.

The high use of electricity in both VIG and IGU manufacturing is attributed to the glass-making stage, which is the primary component of both processes. The high-temperature requirement for glass smelting and the continuous operation required for the glass furnace demands significant energy input. In the process analysed in this study, this energy input is provided using electricity.

Turning to the energy results, the highest embodied energy for VIG manufacturing is attributed to gas extraction and hard coal sector. Natural gas extraction, particularly in the USA, is energy-intensive, since techniques such as hydraulic fracturing are employed. This method heavily relies on diesel-powered machinery for drilling, extraction, and processing of natural gas, exacerbating the overall energy footprint of the gas extraction sector.

Moreover, the float/annealed glass used for manufacturing VIG and IGU requires extreme temperatures often exceeding 1000°C for the smelting process. Natural gas is favoured in this process due to its abundance and relatively lower cost compared to other fossil fuels. In addition, it ensures a stable, reliable, and high-caloric energy output, optimizing heating efficiency in sustaining the required temperatures while reducing production cost.

The electricity sector ranks as the third highest energy consumer across the upstream processes involved in the manufacturing of both VIG and IGU windows. However, the production layer decomposition highlights electricity as the highest energy use in direct impacts for VIG while gas extraction sector remains as the dominant energy consumer within direct and indirect impacts for IGU. As for VIG manufacturing, one of the primary energy-intensive steps is creating and maintaining the vacuum between the glass panes. This process typically involves the use of complex and high-grade vacuum pumps to evacuate the air between the glass panes.

The embodied energy data for IGU, exhibit similar sectoral trends, though with lower overall magnitudes. This difference may be attributed to the additional manufacturing steps involved in producing VIG compared to IGU, such as the installation of support pillars and the application of edge-sealing materials. These processes demand substantial energy inputs, primarily due to the use of automated equipment.

6. Environmental and Economic ROI of VIG Windows

6.1. Environmental ROI

The environmental return on investment (ROI) evaluates how quickly the higher embodied energy of Vacuum Insulated Glass (VIG) is offset by operational energy savings over time, particularly when compared to traditional Insulated Glass Units (IGUs).

Based on performance data and building energy simulation models for residential buildings in cold climates (heating degree days >3500), VIG provides substantial thermal insulation improvements over conventional systems (these building energy data are specific published data for the USA by Arasteh *et al.* 2006):

- VIG thermal conductance: 0.35–0.6 W/m²·K
- Standard double-glazed IGU: ~1.3 W/m²·K
- Triple-glazed IGU: ~0.7 W/m²·K

This represents an improvement of approximately 55–73% over double-glazed IGUs and 15–50% over high-performance triple-glazed IGUs (in both cases the IGU utilises LowE coatings and Argon gas fill).

Annual energy savings in cold climate applications are estimated as follows, relative to a standard double-glazed IGU [**Fout! Bladwijzer niet gedefinieerd.**]:

- Heating energy savings: 120–180 kWh/m²·year
- Cooling energy savings: 15–30 kWh/m²·year
- Total operational energy savings: 135–210 kWh/m²·year

When converted to primary energy using average system efficiencies and grid factors, these translate to approximately (based on a blended primary energy factor of 2.5–3.0 for electricity and 1.1 for natural gas, reflecting average USA grid and heating system mix):

The embodied energy of VIG manufacturing is 524.07 MJ/m², while that of a standard IGU is 106.39 MJ/m². Therefore, the additional embodied energy burden for VIG is approximately 418 MJ/m². Based on the annual energy savings, the energy-based payback period is:

- Primary energy savings: 610–1037 MJ/m²·year
- Minimum payback: 418 ÷ 1037 ≈ 0.40 years (~4.8 months)
- Maximum payback: 418 ÷ 610 ≈ 0.68 years (~8.2 months)

These data indicate that, in cold climates, VIG offsets its additional embodied energy within approximately 5–8 months. In moderate climates, the payback extends to 2–3 years, while in mild climates it may take 5–7 years.

6.2. Economic ROI

The economic ROI considers the cost savings from reduced energy use relative to the higher upfront cost of VIG. Market data indicate:

- VIG cost premium: \$150–200/m²
- Cold climate annual savings: \$15–25/m²·year
- Moderate climate savings: \$10–18/m²·year
- Mild climate savings: \$5–12/m²·year

This results in economic payback periods of:

- Cold climates: 6–13 years
- Moderate climates: 8–20 years
- Mild climates: 12–40 years

Assumptions for utility rates (i.e. \$0.15–0.30 kWh) and HVAC load profiles should be clearly stated in applications to contextualize these results.

6.3. Lifetime Benefits

VIG windows have a typical lifespan of 25–30 years, similar to IGUs. Over this lifetime, the cumulative operational savings and climate benefits are significant:

- Lifetime energy savings: 15,174–29,876 MJ/m² (over 25 years)
- Lifetime GHG reduction from energy savings: 910–1,793 kg CO_2e/m² (over 25 years)

These results demonstrate that while VIG has a higher initial environmental and financial cost, it delivers significant long-term energy savings and carbon reductions, especially in colder regions where energy demand is highest. Here we use a USA blended conversion factor of 0.06 kg CO_2e MJ^{-1}.

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