Challenging Glass Conference Proceedings – Volume 10 – June 2026 – Louter, Bos & Belis (Eds.)
International Conference on the Architectural and Structural Application of Glass
Challenging Glass Conference 10 – 15-17 June 2026 – TU Delft – The Netherlands

Analysis of the Life Cycle Energy Impacts of Vacuum Insulated Glass in Manufacturing and Sustainable Buildings

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Abstract

Building energy efficiency targets have sharpened focus on the embodied costs of high-performance products. Vacuum Insulated Glass (VIG) offers a centre-of-glass U-value in the range 0.4–1.2 W/m²K — well below that of conventional Insulated Glazing Units (IGU) — but its manufacturing is more energy and process intensive. This paper presents a hybrid Life Cycle Assessment (hLCA) of VIG production across six manufacturing scenarios, combining process-level expenditure data, based on US manufacturing, with the GLORIA multi-regional input-output (MRIO) database. The hLCA base case — high-temperature solder glass edge sealing — yields a total embodied energy of 543.3 MJ/m² and GreenHouse Gas (GHG) emissions of 108.6 kg CO_2-eq/m², approximately 5.1 and 2.3 times the IGU reference values, respectively. Alternative sealing processes (and the respective materials), including ultrasonic soldering/welding, reduce these burdens by up to 37.5% in energy and 28% in GHG. An operational payback analysis across four US climate zones (ASHRAE 1A–5A) shows energy recovery in as little as 0.6 years and an Energy Return on Investment (EROI) of 7.6:1 to 46.1:1 over a 30-year service life. VIG recovers its manufacturing energy investment many times over, where the magnitude of that return depends directly on the sealing technology implemented in manufacturing.

Keywords

Life Cycle Assessment, Vacuum Insulated Glass, Embodied Energy, Energy Return on Investment, Manufacturing Scenarios, Supply Chain

Article Information

- Digital Object Identifier (DOI): 10.47982/cgc.10.747
- Published by Challenging Glass, on behalf of the author(s), at Stichting OpenAccess.
- Published as part of the peer-reviewed Challenging Glass Conference Proceedings, Volume 10, June 2026, 10.47982/cgc.10
- Editors: Christian Louter, Freek Bos & Jan Belis

1. Introduction

Windows in dwellings account for a disproportionate share of building envelope heat loss — up to 60% in poorly insulated stock — despite representing only 15–30% of façade area (Cuce & Riffat, 2015; Jelle et al., 2012). As building energy codes tighten, the embodied cost of the insulation solution matters as much as its operational performance. A recent hLCA study by Ibrahim *et al.* (2025) established the supply-chain-complete embodied energy and GreenHouse Gas (GHG) footprint of VIG and IGU manufacture, using process-level expenditure data of US-based manufacturers linked to the GLORIA MRIO database. That work quantified the baseline embodied burden for the dominant commercial VIG process — high-temperature solder glass edge sealing — and identified electricity-intensive manufacturing steps and their upstream supply chains as the dominant contributors. What it did not address — and what this paper does — is how that burden compares across the principal commercial and emerging VIG manufacturing routes, and whether it is recovered through operational savings over a realistic service life.

VIG achieves its thermal performance advantage through an evacuated inter-pane cavity, supported by a precision pillar (submillimeter spacer elements) array, which eliminates gaseous conduction and convection. Centre-of-glass U-values for commercial VIG sit in the range 0.4–1.2 W/m^2K, against 0.6–1.8 W/m^2K for standard low-emittance IGUs — a conductance reduction of 70% or more. That performance advantage comes with a manufacturing consequence: traditionally, VIG requires high-temperature edge sealing using specialized materials, precise vacuum evacuation, precision pillar production and placement, and the use of specific getter materials, all of which are energy-intensive steps absent from IGU production. Different commercial and emerging sealing technologies span a significant range of energy intensity, so the choice of manufacturing processes is not environmentally neutral.

Six manufacturing configurations are evaluated in this paper — spanning high- and low-temperature solder glass sealing, large-panel high-volume processing, and ultrasonic metal-solder soldering/welding — to establish how sealing technology choice affects the lifecycle profile. The hybrid LCA (hLCA) calculations for each scenario were performed independently using the same GLORIA database and functional unit as Ibrahim *et al.* (2025); the S1 base case results are consistent with that reference, while the remaining scenarios, the operational payback analysis, and the EROI calculations are new to this work. The operational analysis applies a ‘degree-day’ based energy saving calculation across four US climate zones (Miami FL, Phoenix AZ, Chicago IL, Seattle WA) using ASHRAE classifications and 2019 grid carbon intensity data, to determine whether, and how quickly, VIG will recoup the embodied investment considering the range of sealing technologies examined. While Ibrahim *et al.* (2025) quantified baseline impacts, it did not evaluate how manufacturing processes alter lifecycle performance or whether embodied costs are recovered in operation.

2. Methodology

2.1. Hybrid LCA Framework

All hLCA calculations reported in this paper were performed independently for each of the six manufacturing scenarios described in Section 2.2. The embodied energy and GHG values for the S1 baseline are consistent with those reported in Ibrahim *et al.* (2025), which used the same GLORIA database and functional unit; the scenario analysis, operational payback calculations, and EROI results are new to this work.

The methodology follows the hLCA approach consistent with ISO 14040, integrating bottom-up process inventory data with a top-down environmentally extended multi-regional input-output (EE-MRIO) model. The process component captures direct energy and material flows within the manufacturing system boundary; the MRIO component — drawn from the GLORIA database (2019), covering 164 regions and 120 industry sectors — extends that boundary across the full upstream supply chain, eliminating the truncation errors inherent in process-only LCA (Pomponi & Lenzen, 2018; Malik et al., 2015).

The functional unit is 1 m² of glazing at the factory gate. Environmental footprints are computed using the standard EE-MRIO formulation: the product of direct environmental intensities, the Leontief inverse, and the final demand vector representing the manufacturing expenditure per functional unit. A production layer decomposition (PLD) approach disaggregates results by upstream supply chain tier. Full methodological detail and the concordance mapping between expenditure categories and GLORIA sectors are given in Ibrahim et al*.* (2025).

2.2. Manufacturing Scenarios

Six scenarios are evaluated, reflecting the principal sealing technologies in current and emerging commercial VIG production. Table 1 sets out the production parameters common to all scenarios. The S1 baseline uses high-temperature solder glass sealing (~450°C); S2 employs low-temperature solder glass (~300°C); S3 combines S2 sealing with large-panel waterjet cutting to reduce glass handling losses, where smaller units are 'cut-out' of a larger multizone panel, similar to multi-panel 'mother glass' processing techniques used in flat panel display manufacturing, where multiple units are fabricated on a single substrate and subsequently separated (e.g., US20060254831A1), and S4a, S4b, S4c replace solder glass entirely with metal solder joined to the glass using an ultrasonic soldering/welding technique, using one, four, and six welder heads per panel, respectively. The S4 variants differ in capital configuration and throughput but share essentially identical energy intensity, since the edge sealing process operates at quite low duty cycles. The IGU reference uses a standard double-glazed unit with Aluminium spacers, Argon fill, and dual sealant infill at the edge, under North American manufacturing conditions, and is included as a performance benchmark only.

Table 1: VIG and IGU production parameters. Functional unit: 1 m² at factory gate. IGU is included as a performance reference only; the primary analysis concerns VIG.

Parameter	**VIG**	**IGU**	**Unit**
Annealed glass thickness	4	4	mm
Unit area (functional unit)	1.0	1.0	m²
Annual production	300,000	479,104	units/yr
LCA functional unit	1 m²	1 m²	--

2.3. Operational Energy Analysis

Operational energy savings are estimated for four US climate zones — Miami FL (Zone 1A), Phoenix AZ (Zone 2B), Chicago IL (Zone 5A), and Seattle WA (Zone 4C) — using ASHRAE classifications and 2019 degree-day data. Annual energy savings per unit area are proportional to the U-value difference between VIG (0.4 W/m²K) and the IGU reference (1.8 W/m²K), applied to heating and cooling degree-day data.

The IGU benchmark used in this study represents a conventional double-glazed low-emittance insulating unit commonly deployed in residential and commercial construction. High-performance triple-glazed systems can achieve lower U-values in the range of 0.5–0.6 W/m²K, which would reduce the relative operational advantage of VIG. However, such systems also carry higher embodied material and manufacturing burdens than conventional IGUs. The primary focus of this work is the comparative influence of VIG manufacturing routes on lifecycle performance, rather than a complete market-wide comparison across all advanced glazing technologies.

In this work, annual carbon emission reductions are estimated by multiplying the energy savings by the regional grid carbon intensity for each zone. Energy payback is defined as the point at which cumulative operational energy savings equal the hLCA-derived embodied energy for the scenario; carbon payback is defined equivalently, using the hLCA-derived GHG burden for each scenario against the annual avoided emissions. Furthermore, a 30-year service life is assumed, consistent with industry practice for commercial and residential window systems.

3. Results

3.1. Embodied Energy and GHG Emissions

Table 2 presents the complete hLCA results for all six VIG scenarios alongside the IGU reference. The S1 carries a total embodied energy of 543.3 MJ/m² and GHG emissions of 108.6 kg CO_2-eq/m² — approximately 5.1 and 2.3 times the IGU reference values of 106.4 MJ/m² and 48.0 kg CO_2-eq/m², respectively. The “Base Case” refers to Ibrahim *et al.* (2025) reference, where the S1 result reflects updated parameterization for the high temperature solder glass edge seal. This difference reflects the additional manufacturing steps in the VIG process: the high-temperature sealing furnace, vacuum evacuation system, precision pillar placement, and getter material and activation, all of which involve energy-intensive automated equipment with substantial upstream supply chain burdens.

For VIG, direct manufacturing impacts account for only 17.7% of total embodied energy, with the remaining 82.3% arising from upstream supply chains. For GHG emissions, the split is reversed: direct impacts constitute 77.8% of the total, reflecting the carbon intensity of grid electricity, which in the US relied on natural gas for approximately 38–40% of generation in 2019. The IGU profile differs markedly, with direct energy and GHG shares of 12.9% and 85.9%, respectively, dominated by the carbon intensity of annealed float glass production. These structural differences demonstrate that a process-only LCA would substantially undercount total impacts and misrepresent the relative environmental profiles of both products, highlighting the importance of a hybrid LCA approach.

Table 2: hLCA results for all VIG manufacturing scenarios and IGU reference (1 m² functional unit). Reduction percentages relative to the S1 baseline. Base Case is the unmodified VIG high-temp SG process (hLCA reference), and refers to Ibrahim et al. (2025) reference, and S1 reflects updated parameterization. S1–S4c are the scenario-parameterised results, where IGU shown as external reference only.

Scenario	GHG Direct (kg CO_2-eq/m²)	GHG Total (kg CO_2-eq/m²)	Energy Direct (MJ/m²)	Energy Total (MJ/m²)	Reduction vs Baseline GHG %	Reduction vs Baseline Energy %
Base Case -- High Temp SG	84.51	108.58	96.28	543.33	--	--
S1 -- High Temp Solder Glass	79.90	103.82	96.28	522.44	4.4%	3.8%
S2 -- Low Temp SG (no pre-dry)	73.23	92.12	72.74	402.50	15.2%	25.9%
S3 -- Low Temp + Waterjet	69.30	87.91	69.89	391.62	19.0%	27.9%
S4a -- Ultrasonic Arch A (1/panel)	61.65	77.77	60.60	339.75	28.4%	37.5%
S4b -- Ultrasonic Arch B (4/panel)	61.68	77.89	60.62	340.77	28.3%	37.3%
S4c -- Ultrasonic Arch C (6/panel)	61.69	77.97	60.62	341.45	28.2%	37.2%
IGU Reference (double-glazed)	41.24	48.00	13.69	106.39	--	--

3.2. Outcome of the Manufacturing Scenarios

The various scenario results highlight that manufacturing selection has a direct, quantifiable effect on embodied burden. Moving from the S1 high-temperature baseline to S2 (low-temperature, no pre-drying) reduces total embodied energy by 25.9% and GHG by 15.2%. Adding waterjet panel processing (S3) extends those reductions to 27.9% and 19.0% respectively. The ultrasonic scenarios (S4a–S4c) achieve the largest reductions — 37–37.5% in energy and 28% in GHG — by eliminating the sealing furnace entirely. The three S4 sub-variants are effectively equivalent in environmental terms; differences in embodied energy between them are under 0.5%, arising from minor capital cost differences in welder array configuration. Figure 1 shows a clear reduction in embodied energy across manufacturing scenarios, with the transition to ultrasonic sealing (S4) producing the largest decrease.

Here the reported 37.5% reduction refers to the total embodied energy of the complete VIG product system, not solely the direct edge sealing operation. Although direct factory energy constitutes approximately 18% of the total embodied energy, changes in sealing technology propagate through the wider supply chain captured by the hLCA framework. Eliminating the high-temperature sealing furnace reduces not only onsite electricity demand, but also the associated upstream burdens linked to electricity generation, industrial equipment, process materials, and supporting manufacturing infrastructure. Consequently, the reduction extends across both direct and indirect lifecycle contributions.

Table 3 sets out the manufacturing cost structure alongside the hLCA outcomes. The energy cost reduction from S1 to S4 — from US$13.50/m² to US$8.50/m² — is directly correlated with the embodied energy reduction, since electricity is the primary driver of both manufacturing cost and upstream supply chain burden. The choice of sealing technology is simultaneously a cost decision and an environmental one.

Table 3: Manufacturing cost structure by scenario.

Metric	S1 (High-Temp SG)	S2 (Low-Temp SG)	S3 (Low-Temp + Waterjet)	S4a (Ultrasonic A)	S4b/c (Ultrasonic B/C)
Sealing method	SG ~450°C	SG ~300°C	SG ~300°C	Welding room temperature	Welding room temperature
Energy intensity (kWh/m²)	158.8	120.0	115.3	100.0	100.0
Energy cost – USA ($/m²)	13.50	10.20	9.80	8.50	8.50
Energy cost – Europe ($/m²)	23.03	17.40	16.72	14.50	14.50
Total CAPEX ($/m²)	29.73	25.83	26.52	22.78	23.14–23.38
Saving vs S1	Baseline	13.1%	10.8%	23.4%	21–22%

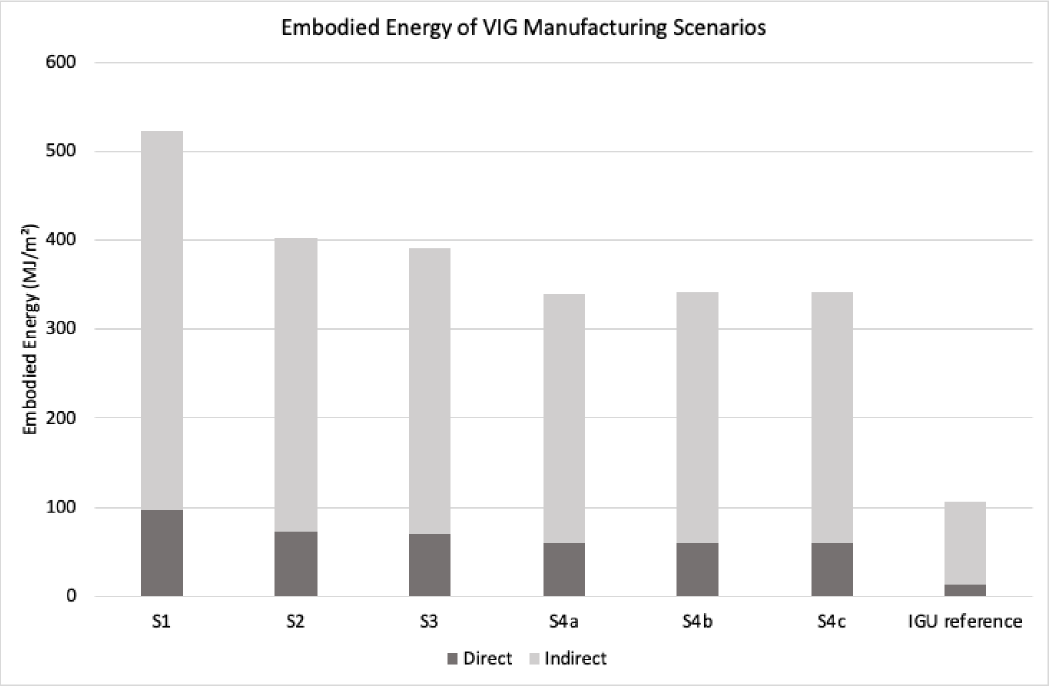

Fig. 1: Embodied energy (MJ/m²) of VIG manufacturing scenarios (S1–S4c) and IGU reference, showing direct (onsite) and indirect (supply chain) contributions. Substantial reductions are achieved through alternative sealing technologies.

3.3. Capital Investment Payback

The manufacturing cost reductions associated with alternative edge seal material and production technologies translate directly into shorter capital investment recovery periods. Figure 2 presents the payback period — defined as the years required to recover total plant setup CAPEX (facility plus equipment) from annual gross profit at a selling price of approximately USD \$65/m² — across the six scenarios and three representative manufacturing markets. For the S1 base case under US manufacturing conditions, the setup investment is recovered in 9.4 years; under European energy pricing, where electricity costs are approximately 70% higher, payback extends to 22.3 years — exceeding the 7-year equipment amortisation horizon. By contrast, the S4a ultrasonic scenario reduces payback to 4.1 years (USA) and 5.2 years (Europe), well within the amortisation period in both markets. The convergence of S4a, S4b, and S4c payback figures across all markets confirms that once the sealing furnace is eliminated, throughput architecture has negligible effect on financial performance. Taken together with the embodied energy reductions in Section 3.1, these results demonstrate that the manufacturing routes offering the greatest environmental benefit simultaneously offer the strongest commercial case — the two objectives are aligned.

The USD \$65/m² selling price used here is conservative relative to current VIG market pricing. Sensitivity analysis shows that doubling the price to USD \$130/m² — while holding all manufacturing costs constant — reduces the S1 payback from 9.4 to 1.9 years (USA) and from 22.3 to 2.1 years (Europe), and the S4a payback from 4.1 to 1.3 years (USA) and 5.2 to 1.4 years (Europe). At higher price points all scenarios converge to under two years across all markets, which further strengthens the commercial case and confirms that the payback conclusions drawn here are not sensitive to the assumed selling price.

4. Operational Energy Return and Payback

4.1. Annual Savings and Payback Periods

The U-value advantage of VIG over IGU — 0.4 vs 1.8 W/m²K considered in this work, a 78% reduction in the centre-of-glass conductance — translates directly into annual operational energy savings that vary with climate. Heating-dominated Chicago produces annual savings of 148.3 kWh/m²/yr, while cooling-dominated Miami yields 37.0 kWh/m²/yr. With S1 carrying 522.44 MJ/m² (145.1 kWh/m²) of embodied energy and S4a carrying 339.75 MJ/m² (94.4 kWh/m²), the energy payback periods are short. In Chicago, S1 achieves payback in approximately one year and S4a in under eight months. Even in Miami — the least favourable climate for VIG due to its modest absolute savings — S1 pays back within approximately four years and S4a within two and a half. Table 4 summarises climate inputs, annual savings, and payback results by zone. Figure 3 illustrates the cumulative operational energy savings relative to embodied energy, highlighting rapid payback across all climate zones and the earlier break-even achieved by ultrasonic sealing.

Table 4: Annual operational energy savings and energy/carbon payback periods for VIG versus IGU across four US climate zones. Energy payback = scenario embodied energy (MJ/m² ÷ 3.6 → kWh/m²) divided by annual savings. Carbon payback = scenario GHG (kg CO_2-eq/m²) divided by annual avoided emissions.

Climate Zone	HDD (°C-d)	CDD (°C-d)	Annual Savings (kWh/m²/yr)	S1 Energy Payback (yr)	S4a Energy Payback (yr)	Grid Intensity (kg CO_2/kWh)	Carbon Payback S1 / S4a (yr)
Miami (Zone 1A)	66	3,900	37.0	~3.9	~2.6	0.485	~5.8 / ~4.3
Phoenix (Zone 2B)	590	3,540	54.5	~2.7	~1.7	0.428	~4.5 / ~3.3
Chicago (Zone 5A)	3,590	720	148.3	~1.0	~0.6	0.425	~1.6 / ~1.2
Seattle (Zone 4C)	2,520	135	100.8	~1.4	~0.9	0.215	~4.8 / ~3.6

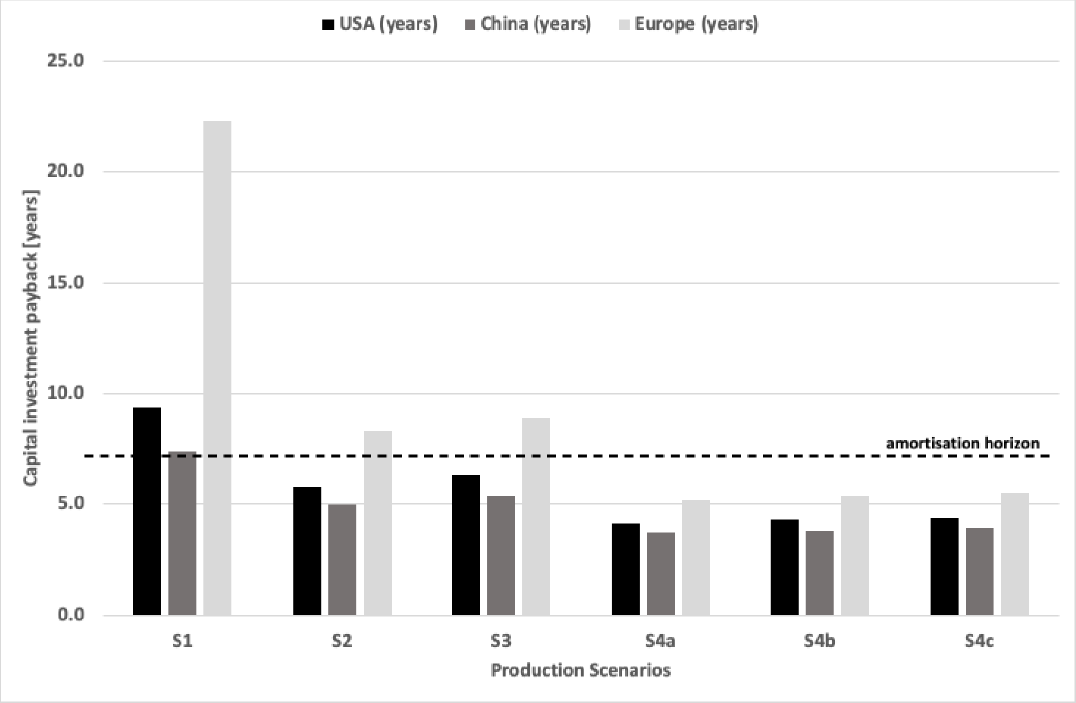

Fig. 2: Capital investment payback period by manufacturing scenario and market (selling price USD 65/m²; 300,000 m²/yr). The dashed line marks the 7-year equipment amortisation horizon. S1 under European pricing (22.3 years) fails to recover within the equipment lifetime; ultrasonic scenarios (S4a–S4c) achieve payback within 5.5 years across all markets.

4.2. Net Lifecycle Return and Energy/Carbon ROI

Table 5 presents the 30-year net energy and GHG savings for S1 and S4a under best-case (Chicago) and worst-case (Miami) climate conditions, together with Energy Return on Investment (EROI) and GHG ROI ratios. The EROI — the ratio of total operational energy saved over 30 years to the manufacturing embodied energy — ranges from 7.6:1 for S1 in Miami to 46.1:1 for S4a in Chicago. The GHG ROI ranges from 5.2:1 to 24.3:1 across the same conditions. In every combination of scenario and climate zone, the operational benefit substantially exceeds the manufacturing cost.

Moving from S1 to S4a reduces embodied energy by 37.5%, which shortens payback periods and raises EROI across all climates. For a manufacturer transitioning to ultrasonic sealing — which also reduces unit CAPEX by approximately 23% relative to S1 — the improvement in lifecycle environmental profile is proportional, with no trade-off against commercial competitiveness.

Table 5: Net 30-year lifecycle energy and GHG savings for VIG S1 and S4a versus IGU reference. EROI and GHG ROI = (30-year operational savings) / (manufacturing embodied burden). EROI and GHG ROI > 1 indicate net positive return. All VIG scenarios and climate zones show strongly positive returns over the 30-year service life.

Scenario / Climate	Energy Payback (yr)	30-yr Net Energy Saving (kWh/m²)	30-yr Net GHG Saving (kg CO₂-eq/m²)	EROI (operational / embodied)	GHG ROI (operational / embodied)
S1 – Chicago (best)	~1.0	~4,304	~1,787	30.7:1	18.2:1
S1 – Miami (worst)	~3.9	~965	~435	7.6:1	5.2:1
S4a – Chicago (best)	~0.6	~4,355	~1,813	46.1:1	24.3:1
S4a – Miami (worst)	~2.6	~1,016	~461	11.8:1	6.9:1
IGU Reference	N/A	0 (baseline)	0 (baseline)	--	--

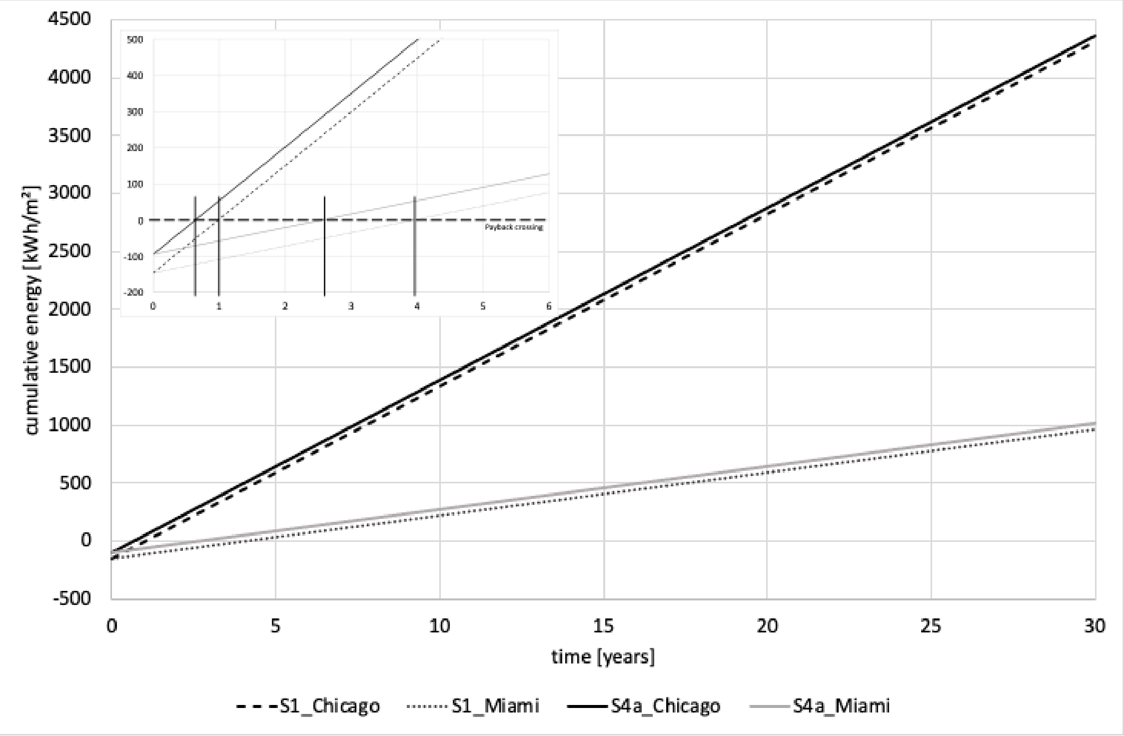

Fig. 3: Cumulative operational energy savings relative to embodied energy for VIG scenarios S1 and S4a across representative climate zones, showing rapid energy payback and strong lifecycle return. The insert plot is a magnification of the payback crossover when cumulative energy is zero.

5. Discussion and Conclusion

This paper has presented a supply-chain-complete hLCA of VIG production across six manufacturing scenarios, with independently calculated embodied energy and GHG footprints for each, and an operational payback analysis across four US climate zones. Three findings from this analysis deserve emphasis.

VIG carries a substantially higher embodied burden than IGU — approximately 5× in energy and 2.3× in GHG — and 82.3% of that energy burden originates in upstream supply chains rather than direct factory operations. The higher GHG ratio relative to Ibrahim *et al.* (2025) arises from updated electricity intensity assumptions and scenario parameterization. These are not modelling artefacts, they reflect the genuine reach of electricity-intensive manufacturing through fossil-fuel-dependent industrial sectors. A process-only LCA analysis would not properly include the dominant share of the impact for both products.

Manufacturing route selection is an environmental variable with the same weight as a cost variable. The 37.5% reduction in total embodied energy from moving to welded edge sealing arises not only from reduced direct manufacturing energy demand, but also from corresponding reductions propagated through the upstream supply chains captured by the hLCA framework. The commercial and environmental cases for the transition point in the same direction.

The embodied burden of VIG is recovered quickly and the lifetime return is strongly positive in every scenario examined. Energy payback ranges from under one year in Chicago to approximately four years in Miami. Over 30 years, the EROI spans 7.6:1 to 46.1:1 in energy and 5.2:1 to 24.3:1 in carbon — meaning the energy and carbon invested in manufacture is returned between 7.6 and 47 times over through avoided operational energy consumption.

These results are directly relevant to building specification and policy contexts where whole-of-life environmental accounting — including embodied carbon — is increasingly required. The data show that the additional manufacturing cost of VIG, both financial and environmental, is recovered within a small fraction of the product's service life across all climates examined.

This analysis uses a degree-day approach to estimate operational savings; solar gain, orientation effects, and whole-building thermal dynamics are outside the present scope. This approach captures first-order conductive heat transfer differences and is appropriate for comparative scenario analysis rather than absolute building energy prediction. The embodied inventory is referenced to 2019 GLORIA data and North American manufacturing cost structures, and results will differ under other grid mixes — particularly for carbon payback in markets with low-carbon electricity. Transportation and end-of-life phases are not included. Extending this framework to non-US manufacturing conditions and incorporating whole-building simulation remain priorities for future work. Within these scope boundaries, the results are unambiguous: across every manufacturing scenario and climate zone examined, the operational energy savings delivered by VIG over its service life substantially outweigh the energy and carbon embodied in its production.

Recent Environmental Product Declarations (EPDs) for commercial VIG products report lower cradle-to-gate greenhouse gas intensities than the hLCA values calculated in this work. For example, Recently AGC/FINEO reported (AGC Glass Europe I, II, 2026) production-stage Environmental Product Declaration (EPD) values in the range of approximately 23–43 kg CO_2-eq/m^2 depending on glazing configuration and low-carbon manufacturing options. These lower values are expected because EPDs and hLCA studies differ in system boundaries, regional electricity mixes, allocation procedures, and the treatment of upstream supply-chain truncation (and specifically in the AGC use of low-carbon glass). The present work intentionally applies a supply-chain-complete hLCA framework to evaluate the relative influence of manufacturing route selection under consistent system assumptions.

VIG carries a higher manufacturing energy and carbon cost than IGU — that much is clear from the hLCA results. What this analysis demonstrates is that this cost is recovered through operational savings across every manufacturing scenario and climate zone examined: in the best case within a single year, in the worst within four, and with a 30-year lifecycle return that is strongly positive in all cases. The choice of sealing technology shapes the magnitude of that return — and notably, the routes that reduce embodied burden also reduce manufacturing cost, so there is no trade-off between the commercial and environmental imperatives. For building designers and specifiers evaluating glazing systems on whole-of-life energy and carbon grounds, VIG makes a compelling engineering case.

Acknowledgements

This work was financially supported by the Australian Research Council (ARC) through Projects IH190100009, DP200103005, LP200100311, DE230101652, LP230201092, and the University of Sydney SOAR Funding.

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Challenging Glass Conference Proceedings – Volume 10 – June 2026 – Louter, Bos & Belis (Eds.)
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