

Article

Life-Cycle Assessment of a CdTe BIPV Glazing Element with Integrated Phase Change Material

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Abstract

This study presents a cradle-to-grave Life-Cycle Assessment of a multifunctional building-integrated photovoltaic (BIPV) skylight system combining a recycled aluminum frame, double-glazing unit, semi-transparent cadmium telluride (CdTe) photovoltaic glass, and an organic phase change material (PCM) for passive thermal regulation. Assessed over a 30-year service life in accordance with EN 15804+A2 using One Click LCA, the system is evaluated across 13 environmental impact categories for a declared unit of 0.72 m². Results show that materials production is the dominant environmental driver across all categories, contributing 72.0% of total GWP (78.00 kg CO₂-eq). Component replacement is the second contributor with 9.8% of GWP. End-of-life burdens account for 7.7% of cradle-to-grave GWP. When Module D credits are included, the system achieves an indicative net GWP balance of −808.34 kg CO₂-eq, that is conditional on a static Romanian grid-mix assumption; under progressive grid decarbonization this benefit is reduced, so the figure should be read as scenario-dependent potential rather than an immutable property of the product. Abiotic depletion of mineral elements is the only category where Module D does not fully offset system burdens, highlighting the relevance of critical raw material considerations for CdTe technologies. These findings demonstrate that BIPV depend on low-impact manufacturing and underscore the importance of multi-indicator LCA as the appropriate evaluation framework for integrated energy-generating building products.

Keywords: building-integrated photovoltaics; cadmium telluride; life-cycle assessment; phase change material; double-glazing; environmental impact; thermal storage; One Click LCA

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1. Introduction

In 2024, buildings accounted for roughly 30% of worldwide final energy use and have been responsible for about one-fifth of the increase in total demand observed since 2019. Within the building stock, the residential segment contributes close to 70% of final energy demand, with the remaining 30% arising from commercial and public buildings [1]. This sustained energy demand keeps the building sector at the center of climate-mitigation strategies, particularly because envelop design decisions influence operational energy use, peak loads, electrification readiness, and the feasibility of integrating on-site renewable generation [1]. Building-integrated photovoltaics (BIPV) represents an approach to reducing building energy demand while generating renewable electricity on-site. Unlike conventional add-on photovoltaic systems, BIPV components serve dual purposes as both

building envelope elements and power generators [2]. In this sense, BIPV should be understood not merely as an energy technology, but as a multifunctional building product whose assessment must account simultaneously for architectural integration, envelope performance, electricity generation, and long-term environmental impacts across the full life cycle [3].

Early life-cycle assessment (LCA) studies on BIPV demonstrated that integrating photovoltaics (PV) into the envelope can substantially improve energy payback time (EPBT) and greenhouse gas (GHG) performance relative to conventional PV and façade systems [4]. More recent work on semi-transparent windows showed that these systems can improve indoor visual and thermal conditions while achieving EPBT values around 13.8 years and GHG payback times of about 10.4 years, both lower than typical service lives, thus confirming net environmental benefits over the life cycle [5]. These findings are important for glazing-integrated systems because they confirm that semi-transparent PV can deliver environmental benefits while preserving daylight admission and façade functionality, thereby strengthening the case for photovoltaic fenestration in high-performance buildings [3]. At the same time, journal-oriented discussion requires moving beyond payback indicators alone, since embodied burdens, replacement schedules, and end-of-life recovery can significantly affect the overall sustainability profile of multifunctional envelope systems when assessed under full cradle-to-grave conditions [6,7].

Recent advances in thin-film photovoltaic technologies, particularly Cadmium Telluride (CdTe) cells, have enabled the development of semi-transparent PV glazing systems suitable for fenestration applications [8]. Simulation studies have demonstrated that integrating semi-transparent CdTe modules into windows can reduce building energy consumption by up to 73% in optimized configurations, while providing satisfactory daylight performance and glare control across different climates [5]. CdTe technology demonstrates superior environmental performance compared to silicon-based alternatives across multiple impact categories, with life-cycle GHG emissions as low as 7.23–15.1 g CO₂-eq/kWh [9,10]. The manufacturing advantages of CdTe, including reduced material requirements, contribute to its favorable environmental profile [11]. The state of the art therefore positions CdTe as one of the most environmentally competitive commercial PV technologies, largely because thin-film deposition requires less semiconductor material and lower upstream energy demand than many crystalline-silicon routes [12,13]. However, the same literature also notes that the environmental interpretation of CdTe systems cannot rely exclusively on operational carbon savings, because semiconductor deposition, critical material use, and end-of-life handling of cadmium- and tellurium-containing components remain key issues in a comprehensive LCA perspective [9,14].

Concurrently, Phase Change Materials (PCM) have emerged as promising thermal energy storage solutions for building applications. PCMs exploit latent heat storage during phase transitions to moderate indoor temperature fluctuations and reduce peak cooling loads [15,16]. Organic PCMs, such as paraffin-based formulations, offer advantages including chemical stability, non-corrosiveness, and favorable phase transition characteristics within building operational temperature ranges [14]. LCA-focused reviews of PCM systems conclude that while PCM manufacturing can introduce embodied impacts, these can be offset by operational energy savings [17]. In building-envelope applications, PCM integration is particularly attractive because it can increase effective thermal inertia without major increases in structural mass, which is valuable for lightweight glazed systems that are otherwise prone to rapid thermal fluctuations [18,19]. Nevertheless, the literature also emphasizes that PCM sustainability is highly sensitive to material type, encapsulation strategy, cycling durability, and replacement frequency, meaning that thermal benefits observed during operation do not automatically translate into a superior life-cycle profile [18].

Most existing LCA studies treat BIPV and PCM technologies separately; only a few conceptual or simulation-based works discuss PCM as a thermal regulator for BIPV, and these do not include a full cradle-to-grave LCA of a physically realized integrated BIPV–PCM skylight window prototype, which defines the specific research gap addressed by this study. This gap is not only empirical but also methodological. BIPV–PCM assemblies are inherently multifunctional systems in which a single construction element simultaneously acts as a transparent or semi-transparent envelope component, a solar electricity generator, and a passive thermal-storage device. As a result, simplified assessments that isolate only one function or only one life-cycle stage risk underestimating trade-offs between embodied impacts and operational benefits [3,7]. The need for a full-system, cradle-to-grave assessment is especially strong for journal-level contributions, because the environmental merit of such hybrid systems depends not only on renewable electricity generation, but also on manufacturing burdens, transport logistics, maintenance and replacement events, and realistic end-of-life scenarios including recycling and recovered-energy credits [6,14].

The integration of PCM with BIPV systems presents two advantages simultaneously: (1) thermal management of PV modules to maintain optimal operating temperatures and electrical efficiency, and (2) building thermal load reduction through passive energy storage [20]. However, the environmental implications of such integrated systems require comprehensive assessment through LCA methodologies to ensure that environmental benefits during the operational phase are not offset by impacts during manufacturing, installation, or end-of-life stages [21]. This dual-performance logic makes BIPV–PCM systems particularly relevant in the transition toward low-carbon and energy-flexible buildings, where envelope components are increasingly expected to deliver multiple services at once rather than satisfy only a single performance criterion [1]. Yet, despite this relevance, current evidence remains fragmented, with much of the published work centered on thermal or electrical performance simulations rather than harmonized environmental assessment using internationally recognized LCA frameworks [6,7].

Despite growing research interest in BIPV and PCM technologies individually, limited studies have examined the complete life-cycle environmental performance of integrated systems combining semi-transparent PV glazing, skylight window systems, and PCM thermal storage. This knowledge gap is particularly significant given the increasing deployment of multifunctional building envelope components in sustainable construction practices. The lack of robust case-specific LCA evidence limits the ability of designers, researchers, and manufacturers to determine whether the environmental gains associated with multifunctionality are sufficient to compensate for the added material complexity of such systems. It also constrains the development of design guidelines for optimizing material selection, service life, and end-of-life pathways in next-generation BIPV glazing products [3,7].

This study presents a cradle-to-grave LCA of an integrated building system designed, with the primary objective of evaluating how individual life-cycle stages contribute to the system's total environmental burden. The system consists of a double-glazed skylight window housed within recycled aluminum frames, enhanced by a multi-layered external configuration. In this setup, the organic PCM is positioned directly on the exterior surface of the double-glazing. The semi-transparent CdTe PV glass is then placed as the outermost layer, effectively sandwiching the PCM between the window and the PV glass. This configuration is particularly relevant from a research perspective because it combines three functions that are often studied separately—daylighting and weather protection, on-site renewable electricity generation, and latent thermal storage—within a single envelope assembly. Assessing such a prototype through LCA provides a more realistic basis for

judging whether integrated solutions can outperform less-coupled alternatives from an environmental standpoint [9,11,18].

The methodological framework of the research relies on ISO 14040/14044:2006 [6] and EN 15804+A2 standards [7] to quantify environmental impacts across thirteen distinct categories. The assessment is performed through the One Click LCA software v. January 2026 (Release 1) platform [22], utilizing the ecoinvent database. The study identifies environmental hotspots across all phases, ranging from the initial product stage encompassing raw material supply to final end-of-life stages. This standards-based framing is essential for positioning the work within the state of the art, because it enables the results to be interpreted in relation to environmental product declaration practice and to other construction-product LCAs that use the same modular logic from product stage to end-of-life and beyond-system-boundary benefits [7].

The novelty of this research lies in the comprehensive assessment of a triple-function integrated building component that simultaneously provides daylighting and view through semi-transparent PV glass, renewable electricity generation via CdTe photovoltaics, and thermal energy storage and PV temperature regulation through PCM integration. The system represents an advanced example of building envelope multifunctionality, where synergistic interactions between components enhance overall performance beyond individual contributions. More specifically, the central problem addressed by this article is the current lack of cradle-to-grave environmental evidence for a physically realized CdTe BIPV glazing element with integrated PCM, despite growing interest in multifunctional envelope technologies for low-carbon buildings. Accordingly, the objectives of the study are to: (i) quantify the environmental impacts of the proposed system over its full life cycle using a declared-unit approach consistent with ISO 14040/14044 and EN 15804+A2; (ii) identify the dominant life-cycle stages and material hotspots across multiple impact categories; and (iii) evaluate whether the integration of semi-transparent CdTe PV glazing and PCM creates a favorable overall environmental profile when recycling and energy-generation benefits are considered.

2. Materials and Methods

2.1. System Configuration

The assessed system consists of a 1200 mm × 600 mm building PV skylight assembly (0.72 m² declared unit) that integrates three primary functional components within a recycled aluminum frame to minimize embodied energy. Figure 1 presents the layer configuration of the studied semitransparent PV module (a), the electrical properties of the studied CdTe PV glass (b), and an experimental test chamber used to assess the electrical performance and impact on indoor comfort of the semitransparent PV skylights (c); the results are presented in [23].

The outermost layer features semi-transparent CdTe thin-film photovoltaic glass, which generates 63 Wp of power while maintaining a 40% transparency rate for natural daylighting and solar control. Positioned between this PV layer and the interior double-glazing is 7.5 L of Rubitherm RT25HC (Rubitherm Technologies GmbH, Berlin, Germany), an organic paraffin-based PCM.

The selected PCM, Rubitherm RT25HC, is an organic, paraffin-based formulation chosen for its phase-transition range centered near 25 °C, which lies within the indoor-comfort temperature band relevant to fenestration applications, and for the favorable latent-heat storage, chemical stability, and non-corrosiveness characteristic of paraffin PCMs. A nominal volume of 7.5 L is integrated within the assembly. Full proprietary thermophysical data are constrained by the absence of a product-specific Environmental Product Declaration (EPD).

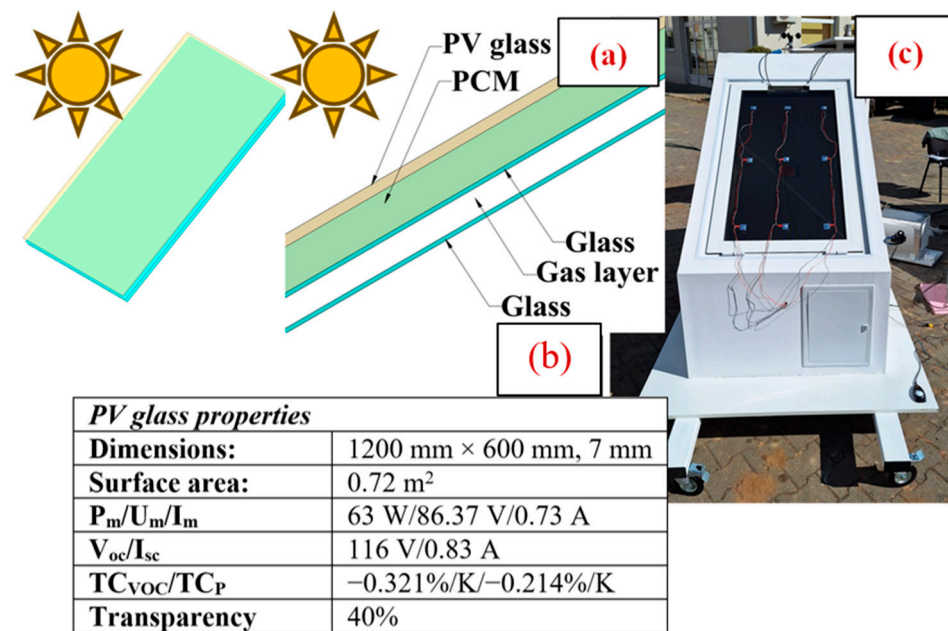


Figure 1. Conceptual representation of the studied building integrated PV glazing module (a), electrical properties (b) and test bench for building integrated PV skylights (c).

This configuration optimizes both thermal and electrical performance. The PCM acts as a thermal buffer, absorbing solar heat gains during the day to reduce peak cooling demands and releasing that energy during cooler periods to stabilize indoor temperatures. Simultaneously, the PCM provides passive cooling for the CdTe layer, lowering operating temperatures to enhance electrical conversion efficiency and extend the system's service life. Therefore, the design achieves a multifunctional building envelope where structural support, renewable energy generation, and advanced thermal management work in coordination.

The experimental test chamber shown in Figure 1c was developed in the authors' previous work [23] to characterize the electrical performance and indoor-comfort impact of the CdTe BIPV skylight under controlled conditions. To avoid ambiguity regarding its role in the present study, we clarify that the LCA inventory reported here is constructed from architectural and material specifications (system geometry, component masses, and service lives), manufacturer data, and ecoinvent background datasets, rather than from direct measurements entered as inventory flows. The experimental stand therefore provides supporting performance context for the assessed configuration; no individual experimental measurement was used as a direct quantitative input to the One Click LCA model. Where instrument-accuracy details are not available to the level of a dedicated experimental report, this is acknowledged transparently here and in [23].

2.2. Goal, Scope and Declared Unit

This LCA study follows the methodological framework established by ISO 14040/14044:2006, supplemented by EN 15804+A2:2019 for sustainability assessment of construction works [6,7]. The goal is to quantify the environmental impacts of the integrated BIPV-PCM skylight window system across its complete life cycle. The study is intended for researchers, building designers, and sustainability practitioners seeking to understand the environmental profile of advanced BIPV envelope systems. It is not intended to support comparative assertions to be disclosed to the public; accordingly, no comparative claim against alternative window or energy systems is made within this work.

The declared unit is defined as one complete window assembly (0.72 m^2), including the recycled aluminum frame, double-glazing system, integrated CdTe photovoltaic glass (63 Wp capacity, 40% transparency), and 7.5 L of Rubitherm RT25HC PCM. A declared unit is adopted in preference to a functional unit because the system delivers multiple simultaneous outputs, electricity generation, passive thermal buffering, and controlled natural daylighting, which cannot be reduced to a single common measure of performance without introducing arbitrary assumptions. The declared unit of one complete assembly (0.72 m^2) therefore provides the most transparent and reproducible basis for environmental quantification in accordance with EN 15804+A2 [7]. In practical terms, this declared unit corresponds to a single standard skylight module ($1200 \text{ mm} \times 600 \text{ mm}$) of the type that can be replicated and tiled across a roof or façade area; reported per-unit impacts can therefore be scaled linearly to the total glazing area of a given building application to support design-stage estimation.

The temporal scope encompasses a service life of 30 years, representing a typical operational period for high-quality window systems in residential and commercial buildings and is also associated with the system's end-of-life phase and final decommissioning. Within this timeframe, the individual components are assigned differentiated service lives based on manufacturer specifications: the CdTe PV glass is assigned a 30-year lifespan; the PCM is assigned a 15-year service life; and the recycled aluminum frame and double-glazing assembly are assigned the full 30-year window lifespan, coinciding with the system's end of life.

Considering the operating period of 30 years, the study assumes that the module undergoes replacement at the end of this period, therefore, this event is modelled simultaneously with the system's end-of-life treatment rather than a separate mid-life event.

2.3. System Boundaries

The system boundaries follow a cradle-to-grave approach, covering the full life cycle from extraction to final disposal.

The product stage (A1–A3) accounts for the manufacturing of recycled aluminum frames, CdTe PV layers, and the PCM. This is followed by the construction process (A4–A5), which includes transport to the site and all necessary installation activities. During the use stage (B1–B7), while operational energy and water consumption are zero, the replacement stage (B4–B5) is critical, accounting for scheduled PCM updates at year 15. As the system reaches its 30-year assessment limit, the end-of-life stage (C1–C4) captures the environmental costs of deconstruction, waste transport, processing, and final disposal. To reflect circular economy impacts, module D separately reports benefits beyond the system boundary. This includes credits for recycling recovered aluminum, glass, and PV materials, as well as the “exported electricity benefit” from 30 years of renewable energy generation, which offsets the system's overall environmental burden. It should be noted that, owing to a limitation of the One Click LCA software, the thermal recovery of the PCM within the assembly was not credited in Module D; consequently, the operational thermal storage benefit of the PCM is treated qualitatively in this assessment.

Minor ancillary materials such as sealants, fasteners, and installation consumables were excluded from the system boundary. These omissions are not expected to materially alter the conclusions of the study given the dominant contribution of the primary structural and energy-generating components.

The geographic scope of the study is Southern Europe, specifically Romania, reflecting the intended deployment context of the assessed system. Background datasets from the ecoinvent database were selected to represent country-specific conditions. The electricity grid mix used for Module D export credits corresponds to the Romanian average, ac-

knowledging that site-specific grid intensity may vary and represents a source of scenario uncertainty discussed in Section 2.4.

2.4. Life-Cycle Inventory

The Life-Cycle Inventory (LCI) employs a hybrid data approach, integrating primary architectural specifications for system dimensions, material mass, and service life with high-fidelity secondary datasets.

Environmental profiles for the recycled aluminum, glass, and CdTe PV modules were sourced from the ecoinvent database to ensure localized technical accuracy.

In the absence of a specific EPD for Rubitherm RT25HC, a paraffin proxy was utilized. This choice is justified by the chemical congruency between paraffin-based commercial PCMs and the bulk paraffin represented in the proxy dataset, so the embodied-impact intensity per unit mass is expected to be of the correct order of magnitude. The proxy does not, however, capture encapsulation materials, performance additives, or the exact industrial production route of the commercial product, which introduces uncertainty in the absolute PCM burden. Because component durability—and therefore PCM replacement frequency—is the PCM-related assumption with the greatest influence on the life-cycle result, the sensitivity of the overall outcome to this assumption is quantified explicitly through the PCM service-life scenarios (10, 15, and 20 years).

The overall data quality is characterized as robust for primary structural and energy-generating components, and moderate for the thermal storage medium.

Life-cycle modeling and environmental impact calculations were conducted using One Click LCA, a globally recognized software platform specialized for the construction sector. Within this study, One Click LCA was used to assemble the declared-unit model from the component inventory, to attach the corresponding ecoinvent and verified-EPD background datasets, and to compute results module-by-module across the full EN 15804+A2 stage structure (A1–A3, A4, A5, B1–B7, C1–C4, and the supplementary Module D). The software environment was configured for the Romanian/European geographic context, and its EPD- and ecoinvent-based datasets ensure traceable, standard-compliant characterization factors. The software ensures compliance with the EN 15804+A2 and ISO 14044 standards by utilizing a vast database of verified EPDs and integrated LCI datasets [6,7,22]. This tool was selected for its ability to model complex building assemblies and provide high-fidelity results tailored to European sustainability frameworks. No experimental measurement was entered into as a direct LCA inventory flow; all quantitative inputs derive from system geometry, material masses, component service lives, transport distances, and end-of-life scenarios.

Transport of materials to the construction site (Module A4) was modelled assuming road freight over an average distance of 300 km for the aluminum frame and glazing components, and 2300 km for the PCM, reflecting the supplier's location to Romania. The CdTe PV module, sourced from the United States of America, was modelled using a multi-modal transport route consisting of 3600 nautical miles by transoceanic sea freight and 2000 km by road. A Euro VI lorry with a loading capacity of 16–32 tones was assumed as the representative transport mode. Installation activities (A5) were modelled based on estimated on-site labor and equipment use, with machinery energy consumption derived from ecoinvent datasets for construction machinery operation.

End-of-life scenarios for each material stream were defined based on current European waste management practices. The recovery assumptions adopted in the base case, which also define the reference point for the sensitivity analysis in Section 3.5, are as follows: recycled aluminum was assumed to have a recycling rate of 95%, consistent with industry-reported recovery rates for architectural aluminum profiles. Glass was assigned a recycling

rate of 80%, reflecting standard flat glass recovery in Europe. CdTe PV modules were modelled under a dedicated PV take-back scheme with 90% material recovery, in line with the Directive 2024/884 provisions for photovoltaic panels [24,25]. The PCM was assumed to be sent to energy recovery (incineration with energy recovery) in the absence of an established paraffin-based PCM recycling pathway. Residual fractions not recovered were allocated to controlled landfill disposal (C4). Waste transport distances to processing facilities (C2) were assumed to be 20 km by road.

2.5. Impact Assessment Method

Environmental impacts were assessed across key categories defined by the EN 15804+A2 standard. The selected impact categories span six environmental domains: climate change, stratospheric ozone depletion, photochemical ozone formation, acidification, eutrophication, abiotic resource depletion, and water use. Together, these indicators provide a comprehensive picture of the pressures exerted by the system under study across different environmental compartments. By adhering to the +A2 amendment of EN 15804 [7], this study provides a more granular breakdown of carbon flows and eutrophication pathways than previous versions of the standard, allowing for a precise identification of environmental hotspots within the product life cycle.

Climate change impacts are captured through Global Warming Potential (GWP), which is reported as a total figure alongside three sub-categories, namely fossil, biogenic, and land use/land use change (LULUC), enabling a detailed understanding of the distinct sources driving greenhouse gas emissions. Atmospheric concerns are further addressed through Ozone Depletion Potential (ODP) and Photochemical Ozone Creation Potential (POCP), the latter tracking the formation of ground-level smog. Nutrient enrichment and chemical imbalances are evaluated through Acidification Potential (AP) and Eutrophication Potential (EP), the latter disaggregated into freshwater, marine, and terrestrial spheres to reflect the different nutrient pathways and receiving environments involved. Resource scarcity is addressed through Abiotic Depletion Potential, split between non-fossil elements and fossil fuels, and total Water Use completes the indicator set by accounting for net freshwater consumption across the life cycle.

With respect to the operational phase, operational energy and water use (Modules B6–B7) were modelled as zero for the declared unit. The renewable electricity generated by the CdTe PV component over the 30-year service life therefore enters the assessment exclusively through the Module D “exported electricity benefit,” where it is credited against the average grid mix. The passive thermal-storage function of the PCM, which is expected to reduce peak cooling demand and stabilize PV operating temperature, is reflected qualitatively in the interpretation (Section 4.3) but is not credited as an avoided operational burden.

Results are interpreted through a life-cycle stage contribution analysis, identifying the relative share of each module (A1–A5, B4–B5, C1–C4, D) in the total impact per category. This is complemented by a material-level hotspot analysis to distinguish the contributions of the aluminum frame, CdTe PV glass, and PCM components. The net environmental balance is assessed by comparing the cradle-to-grave burden (A–C) against the Module D credits, providing a measure of the system’s overall environmental competitiveness when circular economy and energy generation benefits are accounted for.

Table 1 summarizes each category, its abbreviation, unit of measure, and the specific environmental phenomenon it quantifies. The corresponding absolute results by life-cycle stage are reported in Table 2, and a material-level breakdown of the dominant product stage is provided in Table 3.

Table 1. Environmental impact categories assessed in accordance with EN 15804+A2.

Impact Category	Abbreviation	Unit	Description/Scope
Global Warming Potential—Total	GWP total	kg CO ₂ -eq	Cumulative GHG emissions contributing to climate change
Global Warming Potential—Fossil	GWP fossil	kg CO ₂ -eq	GHG emissions originating exclusively from fossil fuel combustion and extraction
Global Warming Potential—Biogenic	GWP biogenic	kg CO ₂ -eq	GHG emissions and removals linked to biogenic carbon cycles
Global Warming Potential—Land Use & Land Use Change	GWP LULUC	kg CO ₂ -eq	GHG emissions associated with changes in land use and land cover
Ozone Depletion Potential	ODP	kg CFC-11-eq	Potential degradation of the stratospheric ozone layer due to halogenated substance emissions
Photochemical Ozone Creation Potential	POCP	kg NMVOC-eq	Contribution to ground-level smog formation through reactions between NO _x and volatile organic compounds
Acidification Potential	AP	mol H ⁺ -eq	Potential acidification of soil and water bodies caused by atmospheric deposition of acid-forming compounds
Eutrophication Potential—Freshwater	EP freshwater	kg P-eq	Excess nutrient loading (phosphorus) that promotes algal growth and depletes oxygen in freshwater ecosystems
Eutrophication Potential—Marine	EP marine	kg N-eq	Excess nutrient loading (nitrogen) that promotes algal growth and oxygen depletion in coastal/marine environments
Eutrophication Potential—Terrestrial	EP terrestrial	mol N-eq	Excess reactive nitrogen deposition that alters nutrient balance and biodiversity in terrestrial ecosystems
Abiotic Depletion Potential—Elements	ADP elements	kg Sb-eq	Depletion of non-renewable mineral and metallic resources, referenced against antimony scarcity
Abiotic Depletion Potential—Fossil Fuels	ADP fossil	MJ	Depletion of non-renewable fossil energy carriers (coal, oil, natural gas), expressed as lower heating value
Water Use	WU	m ³	Net consumption of freshwater resources over the life cycle, accounting for both withdrawals and returns

Table 2. Absolute LCA results per impact category across life-cycle stages (declared unit: one window assembly, 0.72 m², 30-year service life). Module D values are informative and excluded from totals per EN 15804+A2.

Impact Category	Unit	A1–A3 Materials	A4 Transport	A5 Construction	B4–B5 Replacement	C1–C4 End of Life	Total (A–C)	Module D	Net (incl. D)
GWP total	kg CO ₂ -eq	78.00	1.53	9.97	10.57	8.34	108.41	−916.75 *	−808.34 *
GWP fossil	kg CO ₂ -eq	78.10	1.53	9.46	10.57	8.33	107.99	−915.36 *	−807.37 *
GWP biogenic	kg CO ₂ -eq	−0.16 *	0.00	0.50	0.00	0.003	0.34	0.00	0.34
GWP LULUC	kg CO ₂ -eq	0.0764	0.0001	0.0114	0.0014	0.0047	0.0940	−1.39 *	−1.296 *
ODP	kg CFC-11-eq	5.91×10^{-6}	3.59×10^{-7}	8.04×10^{-7}	3.38×10^{-7}	1.54×10^{-6}	8.95×10^{-6}	$-7.7 \times 10^{-5} *$	$-6.78 \times 10^{-5} *$
AP	mol H ⁺ -eq	0.423	0.0025	0.059	0.0265	0.0243	0.535	−4.29 *	−3.775 *
EP freshwater	kg P-eq	1.46×10^{-3}	1.02×10^{-4}	3.52×10^{-4}	9.56×10^{-5}	4.23×10^{-4}	2.43×10^{-3}	−0.122 *	−0.119 *
EP marine	kg N-eq	0.0780	0.0003	0.0094	0.0004	0.0048	0.0929	−0.742 *	−0.649 *
EP terrestrial	mol N-eq	0.760	0.0033	0.111	0.0039	0.0527	0.931	−7.57 *	−6.639 *
POCP	kg NMVOC-eq	0.226	0.0014	0.0315	0.0183	0.0175	0.295	−2.12 *	−1.825 *
ADPE	kg Sb-eq	8.37×10^{-3}	1.08×10^{-2}	2.68×10^{-3}	1.01×10^{-2}	4.78×10^{-3}	3.67×10^{-2}	$-7.4 \times 10^{-4} *$	3.59×10^{-2}
ADPF	MJ	1040	42.9	150	448	132	1813	−11,731 *	−9918 *
Water use	m ³	542	0.00	4.75	25.4	1.50	574	−71,549.8 *	−70,976 *

* Notes: B6 (Energy consumption) = 0 for all categories (no operational energy use). Negative values denote net environmental benefits (carbon sequestration or avoided burdens). ADPE = Abiotic Depletion Potential—elements; ADPF = Abiotic Depletion Potential—fossil fuels; AP = Acidification Potential; EP = Eutrophication Potential (P = freshwater, M = marine, T = terrestrial); GWP = Global Warming Potential; ODP = Ozone Depletion Potential; POCP = Photochemical Ozone Creation Potential.

Table 3. Material-level contribution to the product stage (A1–A3) for GWP-fossil and ADPE (+A2). Percentage shares are derived from One Click LCA’s component-level inventory; absolute values are obtained by applying the percentage to the A1–A3 totals reported in Table 2.

Product Stage	GWP-Fossil (kg CO ₂ -eq)	GWP-Fossil (%)	ADPE (+A2) (kg Sb-eq)	ADPE (+A2) (%)
CdTe PV glass	36.42	46.7	2.277×10^{-3}	27.2
Recycled aluminum frame + double-glazing unit	25.55	32.8	1.267×10^{-3}	15.1
Paraffin-based PCM	16.03	20.6	4.825×10^{-3}	57.7
Romanian electricity (background)	0	0.0	0	0.0
A1–A3 total	78.00	100.0	8.37×10^{-3}	100.0

3. Results

3.1. Global Warming Potential by Life-Cycle Stages

Figure 2 presents the breakdown of GWP results across all life-cycle stages and GWP subcategories (fossil, biogenic, land use and land use change, and total).

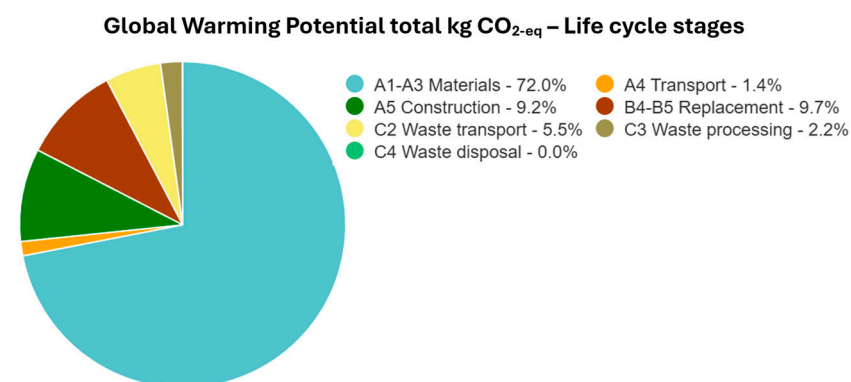


Figure 2. GWP distribution across life-cycle stages.

The cradle-to-grave environmental burden (A1–C4) amounts to 108.41 kg CO₂-eq, a figure that reflects both the material complexity of the integrated BIPV-PCM assembly and the long operational horizon over which replacement and disposal events accumulate.

Unsurprisingly, the production stage dominates the picture. Materials manufacturing (A1–A3) alone accounts for 72.0% of total GWP (78.00 kg CO₂-eq), driven by the energy-intensive processes inherent to three quite different material systems: the electrolytic production of recycled aluminum for the frame, the high-temperature vapour deposition required to form the CdTe photovoltaic layer, and the chemical synthesis of the paraffin-based PCM. That a single life-cycle stage so thoroughly outweighs all others is a characteristic pattern in advanced glazing systems and underscores where design-for-environment efforts would have the greatest leverage.

Construction and installation (A5) contribute a further 9.20% (9.97 kg CO₂-eq), a share that, while secondary, is not negligible and reflects the on-site energy and equipment demands associated with integrating a skylight system of this technical complexity into a building envelope.

The replacement stage (B4–B5) adds 9.75% (10.57 kg CO₂-eq) to the total, arising from the two scheduled interventions during the service life—PCM replenishment at year 15 and PV module replacement at the end of 30-year service life. The close numerical

proximity of this figure to the construction stage (A5) is noteworthy: the environmental cost of maintaining the system over three decades is roughly equivalent to installing it in the first place, which points to component longevity as a meaningful lever for reducing the overall life-cycle burden.

Transport to site (A4) remains a minor contributor at 1.41% (1.53 kg CO₂-eq), consistent with expectations for a relatively compact and lightweight assembly where logistics do not drive the environmental profile.

The end-of-life stages collectively account for 7.69% (8.34 kg CO₂-eq). Within this grouping, waste transport (C2) is the largest contributor at 5.51% (5.97 kg CO₂-eq), followed by waste processing (C3) at 2.16% (2.34 kg CO₂-eq). The near-zero contribution of waste disposal (C4) at just 0.02% (0.03 kg CO₂-eq) is a positive indicator: it reflects effective material diversion through recycling and recovery pathways, meaning that very little of the assembly ends up in landfill at the close of its service life.

3.2. Life-Cycle Assessment

Building upon the GWP analysis presented in Section 3.1, the comprehensive LCA results extend the environmental evaluation across the full suite of thirteen EN 15804+A2 impact categories [7]. Figure 3 presents these results as a normalised stacked-column chart, where each bar represents 100% of the cumulative positive burden (Modules A–C) for a given category. This allows the relative contribution of each life-cycle stage to be compared directly across indicators that operate on different scales. Table 2 complements the figure by providing the absolute values for each stage, including the Module D credits from recycling and renewable energy export that lie beyond the system boundary.

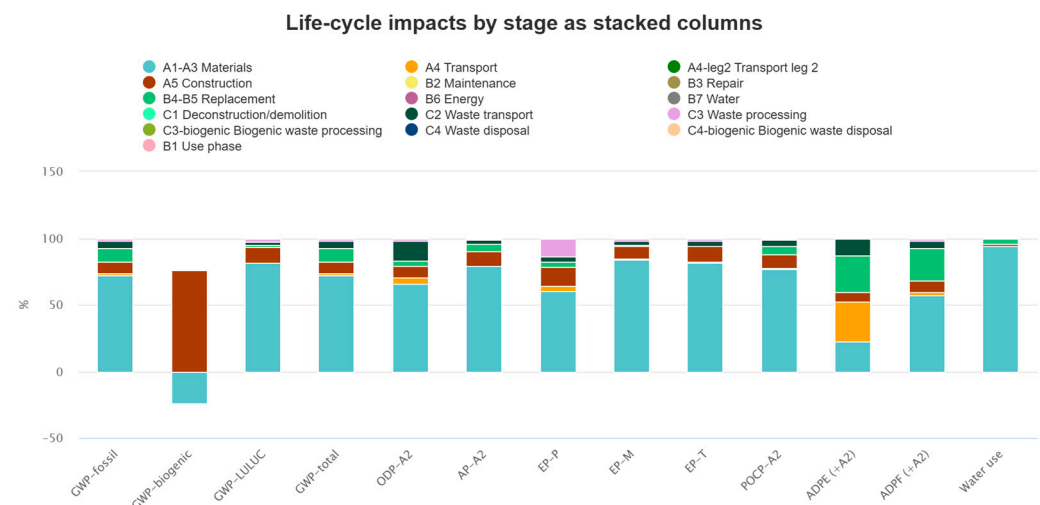


Figure 3. Distribution of environmental impacts across life-cycle stages, normalised to 100% per impact category (absolute values in Table 2). Note: as a 100-normalized composition plot, each bar conveys the relative stage contribution rather than absolute magnitude; error bars are therefore not applied.

Taken together, the two representations show a system whose environmental footprint is overwhelmingly determined by the product stage (A1–A3), representing a significant upfront investment of impacts.

Across most categories, A1–A3 is the single most influential life-cycle stage, and the pattern is striking in its consistency. For marine eutrophication (EP-M), terrestrial eutrophication (EP-T), acidification (AP), and land use (GWP-LULUC), the product stage accounts for between 79% and 84% of the total burden. For water use, it reaches 94.5%, a figure that reflects the significant freshwater demands embedded in CdTe thin-film

deposition and the aluminum smelting process, even when recycled feedstock is used. The implication is clear: if the environmental performance of this system is to be improved, the most productive focus is on the upstream supply chain, particularly the energy sources powering manufacturing and the provenance of the raw materials.

The replacement stage (B4–B5) emerges as the second most significant contributor for fossil fuel depletion (ADPF), where it accounts for 24.7% of the total burden, a share approaching half of what the entire manufacturing stage contributes. This is a consequence of the energy-intensive nature of fabricating replacement CdTe modules at year 30 and replenishing the PCM at year 15. For most other categories, B4–B5 plays a more modest role of 4–10%, but it is never negligible. This finding reinforces the sensitivity of the overall profile to component durability: extending the PCM service life by even a few years would meaningfully reduce the system's mid-life environmental burden.

Construction and installation (A5) contribute consistently to the range of 8–14% across most categories, positioning it as the third largest stage. One category stands apart, GWP-biogenic, where A5 accounts for 75.7% of the total, while A1–A3 registers a negative value of -0.16 kg CO₂-eq. This reversal reflects biogenic carbon dynamics, where the materials stage sequesters biogenic carbon during production of any bio-based components, while construction activities release it through combustion or decomposition processes on site. Although the absolute magnitude of GWP-biogenic (0.34 kg CO₂-eq total) is small relative to GWP-fossil (108 kg CO₂-eq), the sign inversion is methodologically important.

End-of-life stages (C1–C4) collectively account for 7.7% of GWP-total (8.34 kg CO₂-eq), with waste transport (C2) being the dominant contributor within this group. Notably, for ozone depletion (ODP) and freshwater eutrophication (EP-P), the end-of-life share rises to 17%, suggesting that the disposal and processing of CdTe-containing materials carry a disproportionate burden in these categories relative to its modest contribution to climate change. Waste disposal to landfill (C4) remains negligible across all categories at 0.02% of GWP-total, confirming that the end-of-life treatment assumptions—high recycling rates for aluminum, glass, and PV materials—are effective at diverting materials from final disposal.

Abiotic depletion of mineral elements (ADPE) exhibits the most unusual stage distribution of any indicator in this study. Here, transport (A4) accounts for 29.4% and replacement (B4–B5) for 27.5%, together nearly matching the 22.8% contributed by materials production. This reflects the mineral resource intensity embedded in transport infrastructure and the logistics associated with CdTe-related component procurement. Cadmium and tellurium, both classified as critical raw materials, carry significant abiotic depletion characterization factors, meaning that even the transport stages tied to their supply chains leave a detectable mineral resource footprint. Notably, ADPE is the only category where the total cradle-to-grave burden (0.0367 kg Sb-eq) is not fully offset by Module D benefits, resulting in a net positive value of 0.0359 kg Sb-eq.

The most striking finding of the multi-category analysis is the magnitude of the Module D credits. For GWP-total, the 30-year electricity export credit amounts to -916.75 kg CO₂-eq, roughly 8.5 times the cradle-to-grave burden of 108 kg CO₂-eq, yielding a net life-cycle balance of -808.34 kg CO₂-eq. In other words, when the renewable energy generated by the system is credited against the average grid mix, the BIPV-PCM skylight becomes a net carbon sink over its service life. This pattern holds across almost all categories: for water use, Module D generates a credit of $-74,000$ m³, reducing the net balance to $-72,900$ m³; for terrestrial eutrophication, the credit of -7.83 mol N-eq converts a cradle-to-grave burden of 0.93 mol N-eq into a net benefit of -5.97 mol N-eq. The sole exception is ADPE, where the Module D credit (-0.00075 kg Sb-eq) is too small to offset the system burden (0.037 kg Sb-eq), resulting in a positive net value of 0.073 kg Sb-eq. This reflects the fact that the electricity export credit does not capture the mineral resource

value of recovered materials, a known limitation of system expansion applied within the EN 15804+A2 [7] framework.

Because the product stage dominates almost every indicator, a material-level decomposition of A1–A3 was performed to identify which constituents drive the upfront burden across all categories. Figure 4 and Table 3 present this breakdown across the four principal constituents—the CdTe photovoltaic glass, the combined recycled aluminum frame and double-glazing unit, the paraffin-based PCM, and the Romanian background electricity dataset.

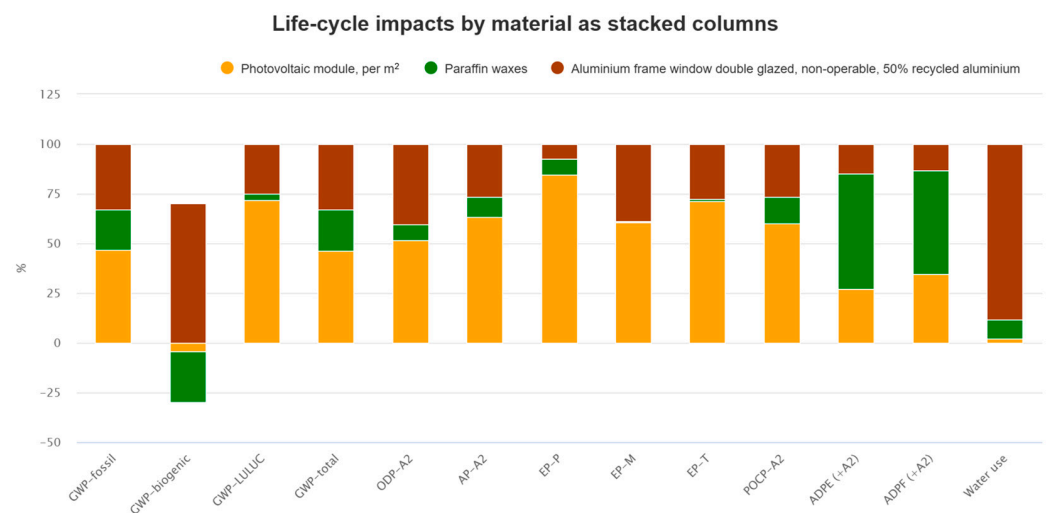


Figure 4. Life-cycle impacts by material contribution to A1–A3 expressed as percentage shares across all 13 impact categories.

Table 3 summarizes and indicates the absolute values for GWP-fossil and ADPE presented in Figure 4, with the raw output data for all 13 impact categories being available from the authors upon request.

For GWP-fossil, the CdTe glass is the single largest contributor (46.7%), consistent with the energy intensity of thin-film vapor deposition; the aluminum frame and double-glazing unit account for a further 32.8%, reflecting the burden of electrolytic smelting of primary and secondary aluminum; and the paraffin-based PCM contributes the remaining 20.6%. For ADPE, the pattern reverses: the paraffin-based PCM is the dominant contributor (57.7%), driven by the mineral-resource characterization factors of the organic synthesis feedstocks, while the CdTe glass accounts for 27.2%, reflecting the criticality characterization factors of cadmium and tellurium embedded in its semiconductor layer. The background electricity dataset contributes negligibly across all categories at the A1–A3 stage, consistent with the zero operational energy assumption of the declared system.

Overall, the multi-category results confirm that the integrated BIPV–PCM skylight performs as designed: it concentrates its environmental costs in the manufacturing phase, carries a manageable mid-life burden from scheduled replacements, and more than offsets both through three decades of clean electricity generation.

3.3. Temporal Evolution of Impacts

The 30-year service life of the integrated BIPV–PCM skylight is characterised by a markedly discontinuous pattern of environmental burden accumulation. Rather than a uniform distribution of impacts across time, GWP-total costs are concentrated in three discrete events, separated by extended impact-free operational intervals, as illustrated in Figure 5. This temporal structure has direct consequences for how the system’s environmental performance should be interpreted and optimised.

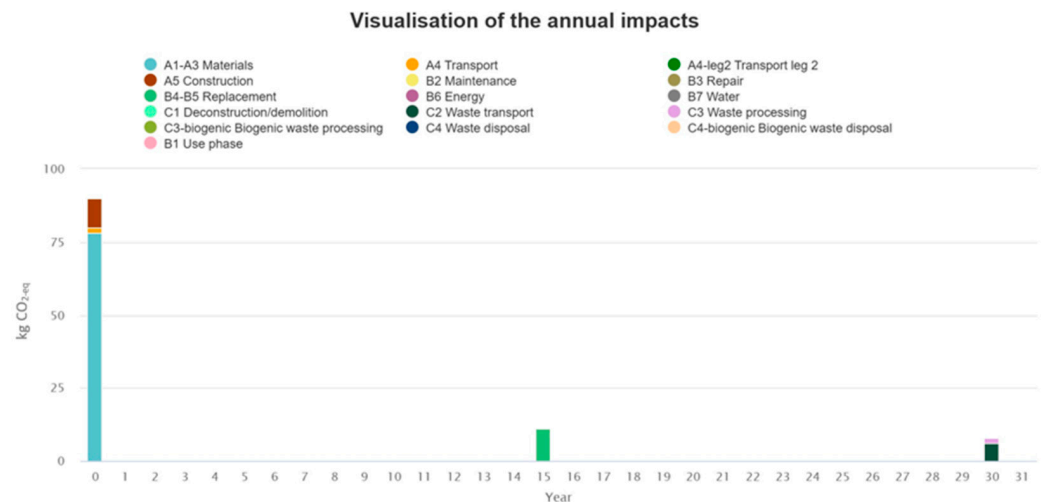


Figure 5. Visualization of the annual impacts.

The first and dominant event occurs at year zero, when materials production, transport to site, and construction and installation converge to generate 89.50 kg CO₂-eq, equivalent to 82.6% of the entire cradle-to-grave burden before the system has entered service. Within this opening phase, materials production alone accounts for 71.9% of the lifetime total (78.00 kg CO₂-eq), driven by the energy intensity of CdTe thin-film deposition, recycled aluminium frame production, and PCM synthesis. Construction activities contribute a further 9.2% (9.97 kg CO₂-eq), while transport plays a minor role at 1.4% (1.53 kg CO₂-eq). Following installation, the system enters a 15-year impact-free operational phase: no operational energy use, no maintenance, and no repair burdens are recorded across stages B1–B3 and B6–B7, reflecting the passive nature of PCM thermal regulation and the zero-emission character of photovoltaic electricity generation.

The second event occurs at year 15, when the PCM reaches the end of its service life and requires replacement. This intervention contributes approximately 3.4% of the lifetime total, a comparatively modest burden consistent with the lower production complexity of organic paraffin-based materials relative to the photovoltaic components. After this replacement, the system returns to impact-free operation for a further 15 years.

The third and final event occurs at year 30, where two simultaneous occurrences are recorded within the same assessment year: the scheduled replacement of the CdTe photovoltaic glass module, which coincides exactly with the end of the system's 30-year service life, and the full end-of-life treatment of all components. This convergence is visible in Figure 4 as a single composite bar combining both B4–B5 replacement and C1–C4 end-of-life impacts. Together, these simultaneous processes contribute 15.21 kg CO₂-eq. Within the end-of-life contribution (8.34 kg CO₂-eq), waste transport (C2) is the largest sub-component at 5.97 kg CO₂-eq (71.6% of end-of-life burden), followed by waste processing (C3) at 2.34 kg CO₂-eq (28.1%). Landfill disposal (C4) is negligible at 0.025 kg CO₂-eq (0.3%), confirming that the high material recovery rates assumed for aluminium, glass, and CdTe are effective at diverting the assembly from final disposal.

The temporal distribution carries a clear design implication: since 82.6% of all life-cycle GWP impacts are locked in at the point of manufacture, environmental improvements are most effectively pursued through upstream interventions, namely the decarbonisation of manufacturing energy sources and the substitution of high-impact materials. The PCM replacement at year 15 represents the only mid-life design lever of material consequence: a PCM formulation durable enough to match the 30-year window lifespan would eliminate this event entirely, reducing the cradle-to-grave burden by the corresponding replace-

ment contribution (B4–B5 attributable to the PCM) while also removing an operational maintenance requirement.

3.4. Benefits and Net Carbon Balance

In accordance with EN 15804+A2, benefits and loads arising beyond the system boundary are quantified and reported separately in Module D. These credits are explicitly excluded from the cradle-to-grave totals (A1–C4) and must not be aggregated with them for the purposes of comparative assessment or regulatory compliance. Module D is provided in the Supplementary Materials to indicate the potential environmental value associated with circular economy processes, specifically the recycling of recovered materials at end of life and across replacement cycles, and with the renewable electricity generated by the PV component over its operational lifetime. The distinction between the A1–C4 system burden and Module D credits is not merely a reporting convention; it reflects a fundamental methodological boundary in EN 15804+A2 [7] between impacts that are attributable to the product system and those that are contingent on downstream decisions made by actors outside it.

For GWP-total, the cradle-to-grave burden amounts to 108.41 kg CO₂-eq. The corresponding Module D credit is −916.75 kg CO₂-eq, yielding an indicative net life-cycle balance of −808.34 kg CO₂-eq when Module D is included. The magnitude of the electricity export credit is the primary driver of this result: the CdTe PV glass generates renewable electricity over 30 years that displaces grid-supplied energy and the associated fossil fuel emissions, with this single credit accounting for approximately 98% of the total Module D benefit. The remaining 2% arises from material circularity, specifically the recovery and recycling of aluminium, glass, and CdTe at end of life and during replacement cycles, with aluminium recovery providing the largest material credit due to the substantial energy savings associated with secondary versus primary aluminium production.

Across the full indicator set, Module D credits exceed the A1–C4 burden in every category except ADPE. For GWP-total, the credit is 8.5 times larger than the system burden; for water use, the Module D credit of −71,550 m³ reduces the net balance to −70,976 m³ against a system burden of 574 m³; for terrestrial eutrophication, the credit of −7.57 mol N-eq converts a cradle-to-grave burden of 0.931 mol N-eq into a net indicative value of −6.639 mol N-eq. The sole exception, ADPE, results in a net positive value of 0.036 kg Sb-eq despite a small Module D credit of −0.00074 kg Sb-eq, because the electricity export mechanism does not capture the mineral resource scarcity value of critical raw materials such as tellurium and cadmium embedded in the transport and manufacturing stages.

The interpretation of Module D results requires explicit acknowledgement of their key sensitivities. The electricity export credit is calculated against the Romanian average grid mix. More significantly, the static LCA framework used here does not account for the progressive decarbonisation of Romanian electricity grids over the 30-year service life: as renewable penetration increases, the marginal carbon intensity of displaced grid electricity will decline, meaning that the actual avoided emissions attributable to the later years of the system's operation will be lower than those modelled here. This effect is quantified explicitly in the dynamic-grid scenario reported in following subsection. Dynamic LCA approaches are increasingly capable of quantifying this effect, and represent a methodological refinement that would strengthen the temporal accuracy of the Module D estimate for future assessments of long-lived building-integrated photovoltaic systems.

3.5. Sensitivity Analysis

To assess the robustness of the principal conclusions and to address the uncertainty inherent in the inventory assumptions, a structured one-at-a-time (OAT) sensitivity analysis

was conducted. Three parameters with the greatest expected influence on the results were perturbed individually around the base case, while all other inputs were held constant: (i) the PCM service life; (ii) the end-of-life recycling rates for aluminum and CdTe; and (iii) the carbon-intensity trajectory of the displaced electricity grid used for the Module D credit.

3.5.1. PCM Service Life

Building on the base case, which assumes a 15-year PCM service life and thus one replacement during the 30-year reference period, two alternative scenarios were modelled: a conservative case with a shortened PCM service life of 10 years requiring two replacements, and an optimistic case with a longer PCM service life of 20 years. The comparison shows that the cradle-to-grave GWP increases from 108.41 kg CO₂-eq in the base case to 118.98 kg CO₂-eq when two PCM replacements are required, while the 20 year replacement scenario leaves the cradle-to-grave GWP unchanged, confirming that mid-life PCM substitution represents a non-negligible but secondary contribution relative to the dominant manufacturing stage. When Module D electricity and recycling credits are included, the net GWP remains strongly negative in all three scenarios (approximately −808 kg CO₂-eq for 15- and 20-year PCM lifetimes and −798 kg CO₂-eq for the 10-year case), indicating that even pessimistic assumptions about PCM durability do not overturn the conclusion that the skylight is climate-beneficial over its 30-year service life, but they do narrow the margin by which avoided emissions exceed embodied burdens. Figure 6 illustrates that PCM service life has a measurable but moderate influence on both the cradle-to-grave burden and the net GWP of the system.

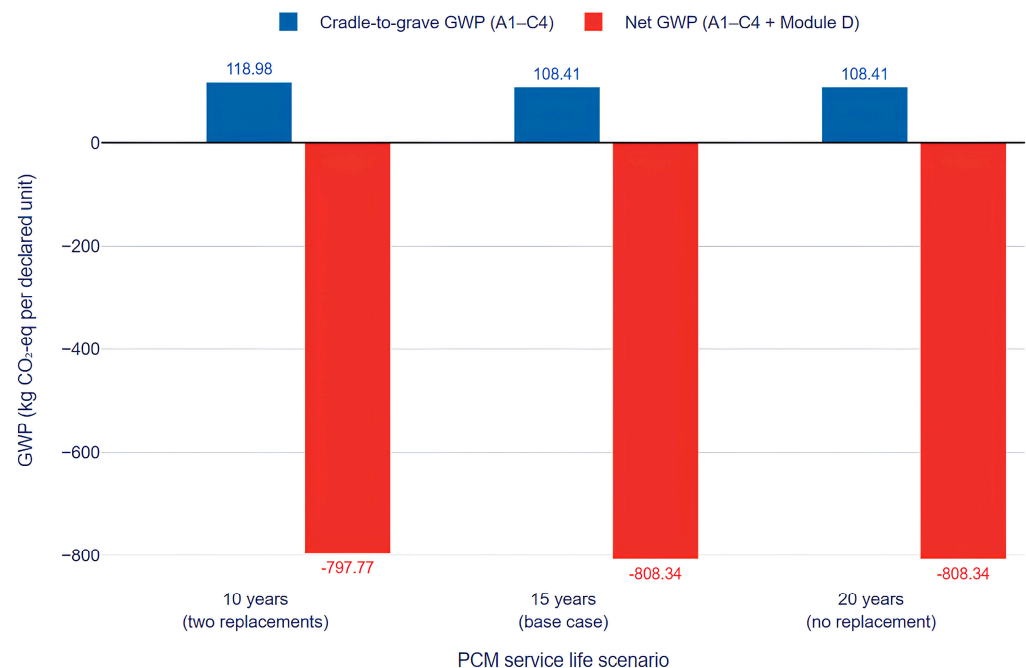


Figure 6. Effect of PCM service life assumption on GWP for the declared unit.

The sign of the net balance—and therefore the system’s classification as a net carbon sink—is preserved across all three scenarios, confirming that the qualitative conclusion of the assessment is robust to uncertainty in PCM durability. The dominant driver of net GWP remains the Module D electricity export credit, which dwarfs the replacement-stage contribution at all three service life assumptions.

3.5.2. End-of-Life Recycling Rates

The base case assumes 95% recovery for aluminium and 90% material recovery for CdTe. Perturbing these recovery rates by -20% to -30% (see Figure 7) reduces the material-circularity component of the Module D credit and slightly increases the residual C4 landfill burden, while higher recovery rates have the opposite effect. Because material circularity accounts for only about 2% of the total Module D benefit—the electricity export credit providing the remaining $\sim 98\%$ —the net GWP balance is comparatively insensitive to the recycling-rate assumption: realistic variations in aluminium and CdTe recovery shift the net GWP by a small fraction of the dominant electricity credit and do not alter the qualitative conclusion that the system is a net carbon sink under the static-grid assumption.

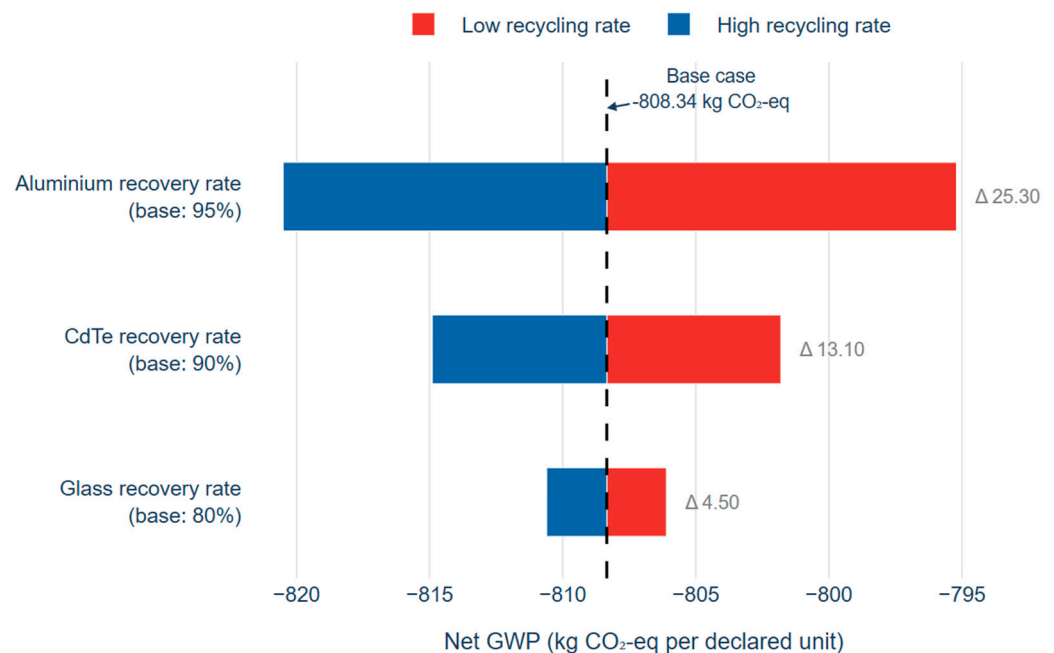


Figure 7. Tornado diagram showing the sensitivity of net GWP to end-of-life material recovery rate assumptions.

The recovery rates exert a proportionally larger influence on the resource-related indicators, where the persistence of a net positive value is robust to the tested range because the small Module D mineral-resource credit cannot offset the embodied critical-material burden even at the upper recovery bound.

3.5.3. Grid Decarbonization

To evaluate the sensitivity of Module D to future electricity-system developments, three time-dependent decarbonisation trajectories were defined for the Romanian grid mix over the 30-year reference service life (Figure 8). The baseline year was fixed to the 2023 grid GWP factor of 0.41 kg CO₂-eq/kWh used in the main One Click LCA model. Building on Romania's updated Integrated National Energy and Climate Plan, Fit-for-55 implementation, and recent EU and IEA power-sector outlooks [26–28], we specified a slow decarbonisation pathway with gradual coal reduction and sustained gas use (S1), a moderate trajectory consistent with achieving the envisaged 2030 and 2050 RES shares and near-complete power-sector decarbonisation (S2), and a fast scenario with accelerated coal phase-out and rapid wind and PV deployment (S3). For each scenario, grid GWP factors in 2030, 2040 and 2050 were anchored to these sources and linearly interpolated to obtain annual values from 2023 to 2052, yielding 30-year average emission factors of approximately 0.29, 0.17 and 0.11 kg CO₂-eq/kWh for S1, S2 and S3, respectively.

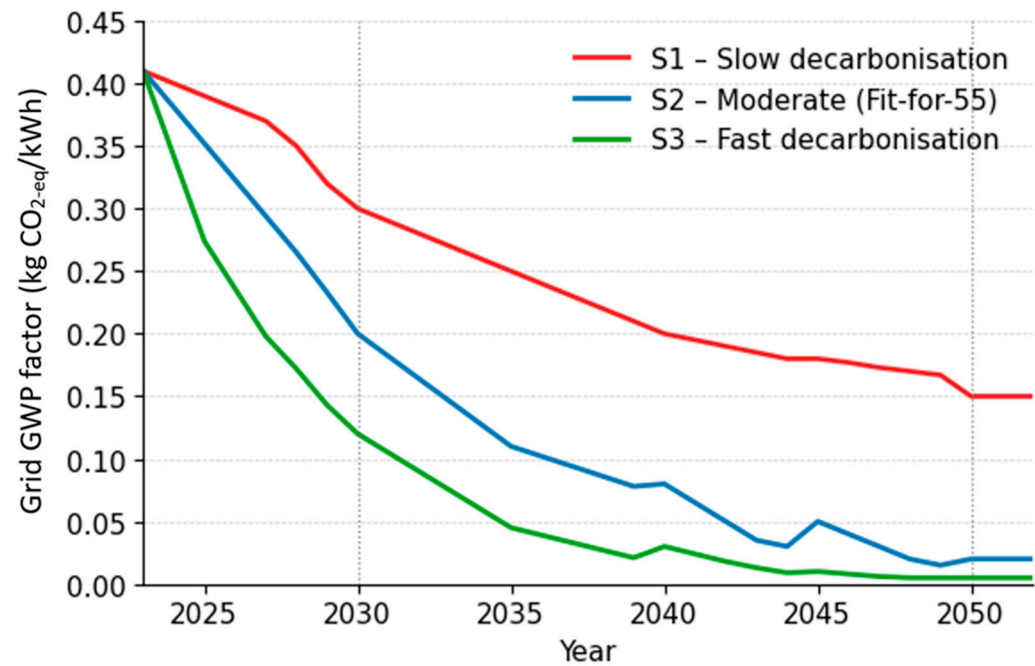


Figure 8. Assumed Romanian electricity-grid decarbonisation trajectories used in the Module D sensitivity analysis.

The avoided burden from exported PV electricity in Module D was then recalculated by multiplying the annual electricity yield of the skylight by the scenario-specific emission factor in each year and summing over the 30-year period. In the static-grid base case, the Module D electricity credit corresponds to a constant factor of 0.41 kg CO₂-eq/kWh and yields the largest avoided GWP, which dominates the net balance when combined with recycling credits. Introducing dynamic, policy-consistent grid trajectories reduces the effective emission factor of displaced electricity as renewables expand, thereby lowering the Module D credit to roughly 70% of the static estimate in the slow-decarbonization scenario, and to around 40% and 25% in the moderate and fast trajectories, respectively. Although the skylight remains net climate-beneficial under all three scenarios, the analysis highlights that the magnitude of Module D is highly sensitive to grid decarbonization assumptions and should therefore be interpreted as a scenario-dependent potential rather than an intrinsic attribute of the product.

4. Discussion

4.1. Overview and Key Findings

The results indicate that the environmental profile of the assessed CdTe BIPV-PCM skylight is governed primarily by upfront embodied impacts rather than by burdens arising during operation, with A1–A3 dominating GWP and most of the other impact categories over the 30-year assessment period. This pattern suggests that the environmental performance of this multifunctional assembly depends more strongly on manufacturing choices, material sourcing, and component durability than on direct in-use burdens, since the use stage itself was modelled with zero operational energy and water demand for the declared unit. Such a profile is characteristic of advanced envelope technologies in which the environmental balance is effectively decided before the system enters service, and it confirms that design-for-manufacture is at least as important as design-for-operation in integrated BIPV concepts [3,29].

A second key finding is the importance of replacement processes, which emerge as the main secondary hotspot after manufacturing. The results show that component replacement

contributes a non-negligible share across several impact categories and becomes especially relevant for fossil resource use, indicating that the environmental viability of the concept depends not only on the initial assembly but also on whether the service lives of the PV and PCM layers are well aligned with the lifespan of the glazing system as a whole. In interpretive terms, this means that the environmental advantage of multifunctionality can be weakened if one of the integrated materials requires premature substitution, because the assembly then inherits recurring burdens that partially erode the benefits of low-impact operation [20,29,30].

The temporal results further reinforce this interpretation by showing that the burden is highly discontinuous and concentrated in a small number of events, especially at installation and at replacement/end-of-life milestones. This temporal concentration is analytically important because it highlights that the system does not accumulate impacts gradually through operation but instead experiences environmental “punctuations” tied to material production, scheduled substitution, and waste handling. From a life-cycle management perspective, the implication is that any improvement in manufacturing efficiency or component longevity will have a disproportionately large effect on total impact, whereas marginal changes in an already negligible use-stage burden will have limited leverage.

Finally, the very large Module D credits indicate that the long-term environmental rationale of the system is strongly linked to avoided burdens from exported electricity and, to a lesser extent, material recovery. This suggests that the system can only be understood properly if both the cradle-to-grave burdens and the beyond-boundary benefits are interpreted together, while still respecting the methodological distinction required by EN 15804+A2 between attributable impacts and potential downstream credits [7]. At the same time, the fact that ADPE remains positive even after Module D is included is a critical result, because it shows that net climate benefits do not automatically imply net benefits for mineral resource depletion when critical materials such as cadmium and tellurium are involved [9,11].

4.2. Positioning Within the Existing LCA Literature

The dominance of the production stage is broadly consistent with the LCA literature on CdTe photovoltaics. Research studies report GWP values for CdTe PV systems ranging from 7.23 to 15.1 g CO₂-eq/kWh, with the CdTe panel contributing approximately 47.8% of total system emissions [14,16]. Multiple studies confirm that CdTe thin film technology demonstrates lower environmental impacts than silicon-based alternatives across most categories [10,11,16]. The present results align with that body of evidence but extend it by showing that when CdTe is embedded in a multifunctional glazing assembly with aluminum framing and PCM, the production hotspot remains dominant despite the increased architectural complexity of the product.

To contextualize these findings against conventional alternatives without overstepping the non-comparative goal of this study, it is useful to note that conventional glazing and non-PCM BIPV systems reported in the literature [31–33] exhibit the same qualitative pattern of manufacturing-dominated burdens, but lack the dual electricity-generation and passive thermal-regulation functions that drive the large Module D credit observed here. The present per-unit results are therefore directionally consistent with published CdTe and BIPV assessments, while the multifunctional integration is what distinguishes the environmental logic of the assessed assembly. This comparison is offered as contextualization only and not as a formal comparative LCA, which would require harmonized functional units and datasets.

The pronounced water-use burden in A1–A3 (94.5%) also agrees with the literature emphasizing the resource intensity of PV manufacturing and glass/aluminum processing.

In this case, the result is particularly meaningful because water use reached its highest concentration in the production stage, implying that the environmental optimization of the system cannot be reduced to carbon mitigation alone. This confirms a recurring point in recent PV LCA research: impact–category trade-offs matter, and technologies that perform well in GWP can still exhibit pressure on water or mineral-resource indicators depending on the manufacturing route and supply chain [34].

The unusual behavior of ADPE deserves particular comparison with prior work. The persistence of a positive net ADPE despite large Module D credits reflects the fact that critical raw materials in thin-film photovoltaics carry high characterization factors that are not fully counterbalanced by avoided electricity production. This is consistent with previous environmental analyses of CdTe that emphasize both its favorable climate performance and the need for careful interpretation of resource-related metrics because tellurium and cadmium occupy a special position in material-criticality discussions [9,11]. In that sense, the present article contributes a useful nuance to the BIPV literature: a system may be net beneficial in carbon terms while still requiring caution from a critical-materials perspective [29,35].

The end-of-life findings are also in reasonable agreement with the recycling literature. The low landfill burden observed in this study, where waste disposal accounts for just 0.3% of end-of-life GWP, and the modest but non-negligible contributions from waste transport and processing (representing 7.4% of the cradle-to-grave total) suggest that the assumed high material recovery rates for aluminum and CdTe components are environmentally effective. This is consistent with Yan and Xiang [29], whose comparative review of BIPV technologies confirms that end-of-life treatment constitutes a relatively minor share of total cradle-to-grave impacts across thin-film systems when adequate recovery infrastructure is in place, and that manufacturing-stage burdens systematically dominate the life-cycle profile, a pattern clearly reproduced in the present results. Regarding CdTe-specific disposal and recycling pathways, dedicated PV take-back and recycling schemes enable the recovery of glass, encapsulant, and semiconductor fractions, including cadmium and tellurium, diverting potentially hazardous material from landfill and partially recirculating critical raw materials. Raj et al. [35] find that the environmental burden of industry-scale CdTe recycling is sensitive to process design, facility location, and the specific recovery efficiencies achieved for cadmium and tellurium, meaning that the absolute magnitude of end-of-life credits and burdens reported in Module D is inherently context-dependent. Taken together, these sources support the interpretation that the recovery pathways assumed in this study are directionally sound, while acknowledging that exact impact magnitudes depend on the specific recycling technologies deployed, transport logistics, and process-level dataset.

In terms of PCM, the results are also coherent with the scientific literature, especially regarding the relevance of service life and replacement frequency. Reviews of PCM applications in buildings note that the environmental desirability of PCM integration is highly sensitive to durability, encapsulation, and the balance between added embodied impacts and operational savings; paraffin-based systems may be advantageous in some applications but can lose environmental competitiveness when replacement is frequent or when operational savings are modest [18,20,36,37]. The present findings support that interpretation: PCM does not dominate the initial burden, but its replacement contributes meaningfully to the life-cycle profile, confirming that durability is a system-level issue rather than a material-level detail.

4.3. Interpretation and Implications

Taken together, the findings indicate that the assessed BIPV–PCM skylight should be interpreted as a manufacturing-intensive but potentially climate-positive envelope

technology. Its environmental logic is not based on low embodied impact; rather, it is based on accepting a relatively concentrated upfront burden in exchange for long-term avoided grid electricity and multifunctional envelope performance. This distinction matters for scientific interpretation because it prevents an overly simplistic conclusion that the system is “low impact” in an absolute sense; instead, it is more accurate to describe it as a system with significant embodied burdens that can become environmentally favorable over time under specific assumptions about service life, electricity substitution, and recovery pathways [21,29,30].

Although the present declared-unit model assigns zero operational energy and therefore does not quantify operational savings itself, the mechanism by which the PCM contributes to operational performance is well established and worth making explicit. By absorbing latent heat during daytime solar gain and releasing it during cooler periods, the PCM is expected to lower peak cooling demand and dampen indoor temperature swings, while simultaneously moderating the CdTe operating temperature and thereby supporting electrical conversion efficiency. Quantifying these operational savings is beyond the scope of the present LCA and requires coupling the assembly to a dynamic building-energy simulation.

The strong role of the production stage implies that design optimization should focus first on upstream interventions. In practice, this means prioritizing lower-impact manufacturing electricity, reducing the mass or impact intensity of frame and glazing constituents, improving the material efficiency of the CdTe layer, and selecting suppliers with better environmental performance data. For envelope design practice specifically, three actionable priorities follow from the results: (i) specify components manufactured with low-carbon electricity, since manufacturing energy is the dominant lever; (ii) align the service lives of the PCM and PV layers to avoid mid-life replacement burdens; and (iii) weigh material criticality and recyclability alongside operational decarbonization when selecting thin-film technologies. Such strategies are likely to yield greater environmental returns than downstream optimizations that target already minor stages, and this conclusion is directly supported by the stage-distribution patterns observed in the results. For practitioners, this shifts attention from the common assumption that transport or disposal dominate innovative products toward the less visible but more consequential issue of industrial supply-chain decarbonization.

The Module D findings require especially careful interpretation. On one hand, they indicate that the system may deliver substantial avoided burdens through electricity generation, which strengthens the argument for BIPV as a multifunctional decarbonization measure rather than merely a building product. On the other hand, these credits are scenario-dependent and sensitive to the assumed grid mix over time. As the original manuscript already notes, a static credit based on the Romanian average grid may overestimate long-term avoided emissions if the electricity system decarbonizes during the service life. Therefore, the strong negative net GWP should be interpreted as indicative potential rather than as an immutable property of the product itself.

More broadly, the results underscore the importance of evaluating multifunctional façade and skylight systems with a multi-indicator perspective. If the discussion were limited to GWP alone, the system would appear unequivocally favorable once Module D is considered. However, the persistence of positive ADPE shows that climate and resource indicators can diverge, which is precisely why assessments of emerging building technologies should avoid single-metric conclusions. From a resource-availability standpoint, tellurium is among the scarcest stable elements in the Earth’s crust and is recovered largely as a by-product of copper refining, while cadmium handling raises additional governance considerations; both are routinely flagged in critical-raw-material assessments.

The net-positive ADPE result is thus not merely a characterization artefact but a signal that large-scale deployment of CdTe-based envelopes should be accompanied by secure, circular tellurium supply and robust recovery infrastructure. For design practice, this means that decisions about BIPV glazing should weigh not only operational decarbonization but also resource criticality, recyclability, and durability [9,12,34].

4.4. Limitations

Several limitations should be considered when interpreting the discussion above. First, the analysis is based on one specific prototype configuration and one declared unit, which means the conclusions are directly valid for the assessed assembly but should not be generalized without caution to all BIPV-PCM systems. Variations in glazing area, transparency, PV power density, PCM type, frame composition, orientation, and building context could materially affect the balance between embodied burdens and exported-electricity credits.

Second, the results depend on background datasets and modelling assumptions that introduce uncertainty, particularly for PCM. The use of a paraffin proxy in place of a product-specific environmental dataset is a reasonable modelling strategy in the absence of an EPD, but it reduces the precision with which PCM-related burdens and replacement effects can be interpreted. This limitation is especially relevant because the discussion identifies component durability as a major influence on overall performance; uncertainty in PCM data therefore affects one of the study's central conclusions.

Third, the interpretation of Module D is inherently sensitive to scenario assumptions. The reported credits rely on assumptions about recycling rates, recovered material quality, and displaced electricity impacts, all of which may vary over time and by geography. In particular, if future Romanian or European electricity mixes become less carbon intensive, the magnitude of avoided GWP from exported electricity would decline. The system would still generate renewable electricity, but the environmental credit per kilowatt-hour would be lower than under the static assumption used here.

Fourth, although the results identify hotspots by life-cycle stage, the present study does not resolve all process-level causes with the granularity that might be achieved through a more disaggregated inventory or manufacturer-specific primary data. Specifically, the One Click LCA model resolves the product stage at the level of component/material datasets rather than individual unit processes, so the material breakdown in Figure 4 and Table 3 cannot isolate, for example, vapor deposition from cell metallization within the CdTe dataset. This limits the ability to attribute burdens precisely among the CdTe layer, glazing processes, aluminum frame production, encapsulation materials, and installation activities. As a result, the discussion can identify strategic directions for improvement, but not yet a fully optimized redesign pathway supported by process-level sensitivity analysis. Relatedly, the sensitivity analysis in Section 3.5 is a structured one-at-a-time scenario perturbation rather than a probabilistic propagation; a full Monte Carlo uncertainty analysis was not feasible because the background datasets do not provide the per-flow uncertainty distributions it requires. Probabilistic propagation using inventories that carry such distributions is identified as future work.

Finally, the study is environmentally in scope and does not address economic viability, indoor comfort trade-offs, toxicity-risk governance, or social dimensions. For a multifunctional technology intended for building integration, those dimensions are highly relevant to real-world adoption. A product may be environmentally promising in LCA terms while still facing barriers related to cost, maintenance complexity, user acceptance, regulatory constraints, or perceived risk associated with cadmium-containing materials. Life-cycle

costing and techno-economic assessment are therefore identified as priority complementary analyses in Section 4.5.

4.5. Future Research Directions

This subsection distinguishes between the authors' own planned next steps and broader recommendations to the research community. Within the ongoing SKYCOOL project, the authors plan to: (i) acquire product-specific PCM inventory data (manufacturer data and, where possible, a product EPD) together with measured maintenance and degradation histories, to replace the paraffin proxy used here; (ii) couple the present LCA with a dynamic building-energy simulation of the prototype so that the operational electricity generation and PCM-driven cooling-load reduction can be quantified rather than treated qualitatively; and (iii) carry out experimental validation of the operational thermal–electrical performance on the test stand, feeding measured performance back into the inventory.

For the wider research community, several complementary directions would strengthen assessments of multifunctional BIPV–PCM systems. First, dynamic and regionalized LCA could better represent changing electricity mixes over the service life and capture regional variability. Second, integrated decision frameworks combining LCA with life-cycle costing (LCC), circularity and criticality assessment, and thermal-comfort analysis would provide a more decision-relevant basis for designers and manufacturers than environmental accounting alone. Third, data-driven and machine-learning-assisted optimization could help balance the competing thermal, environmental, and energy-generation objectives of such assemblies, and physics-informed or solver-based modelling of the coupled thermal–electrical governing equations represents a promising route to predicting the operational PCM–PV behavior that the present static LCA does not resolve. These modelling directions are noted here as prospective avenues; the present contribution remains an environmental LCA, and any future literature integration in these areas should be selected for direct relevance to building envelope LCA.

5. Conclusions

This study presented a cradle-to-grave LCA of a multifunctional CdTe BIPV glazing system with integrated PCM and recycled aluminum framing, assessed over a 30-year service life under the EN 15804+A2 framework. The results show that the system is manufacturing-intensive but potentially climate-positive in a specific quantified sense: A1–A3 accounts for 78.00 kg CO₂-eq, equal to 72.0% of the cradle-to-grave GWP and 94.5% of total water use, while the long-term environmental value arises almost entirely from electricity generation credited in Module D (~98%) rather than from low embodied impacts. This favorable net climate balance is conditional on the static Romanian grid assumption and is reduced under progressive grid decarbonization.

Materials production is the decisive environmental hotspot, with A1–A3 contributing 78.00 kg CO₂-eq, 72.0% of cradle-to-grave GWP, and 94.5% of total water use. This concentration confirms that the primary leverage for environmental improvement lies upstream, in the decarbonization of manufacturing energy and the reduction in impact-intensive material inputs, rather than in marginal refinements to transport or disposal.

Component longevity is the second critical determinant of performance. Replacement processes contribute meaningfully to fossil resource depletion and GWP, reflecting the service-life mismatch between the glazing assembly, CdTe layer, and PCM. Environmental burdens are concentrated in discrete events—installation, mid-life PCM replacement at year 15, and the combined PV replacement and end-of-life phase at year 30—rather than

distributed across operation. Extending PCM durability and improving encapsulation stability are therefore high-priority design strategies.

When Module D is included, the system achieves a net GWP balance of -808.34 kg CO₂-eq, with avoided emissions from exported electricity exceeding the cradle-to-grave burden by a factor of 8.5. This result is conditional on grid carbon intensity and material recovery assumptions and should be read as indicative potential rather than directly attributable product performance. Notably, ADPE remains the only category where Module D does not fully offset system burdens, underscoring that carbon performance alone is insufficient to characterize the sustainability of CdTe-based systems and that multi-indicator assessment is essential.

Future work should prioritize product-specific PCM inventory data, alongside techno-economic and circularity assessments to support practical deployment of multifunctional BIPV envelope systems in low-carbon buildings.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/cleantechnol8040105/s1>, Table S1: Raw data of LCA results per impact category across life-cycle stages.

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Abbreviations

The following abbreviations are used in this manuscript:

LCA	Life-Cycle Assessment
ISO	International Organization for Standardization
EN	European Standard
EPD	Environmental Product Declaration
PCR	Product Category Rules
BIPV	Building-Integrated Photovoltaics
PV	Photovoltaic
CdTe	Cadmium Telluride
PCM	Phase Change Material
EPBT	Energy Payback Time
GHG	Greenhouse Gas
A1–A3	Product stage (Raw material supply, Transport, Manufacturing)
A4	Transport to site
B1–B7	Use stage modules (Use, Maintenance, Repair, Replacement, Refurbishment, Operational Energy Use, Operational Water Use)

B4	Replacement
B5	Refurbishment
C1–C4	End-of-life stage (Deconstruction/demolition, Transport, Waste processing, Disposal)
C2	End-of-life Transport
C3	Waste processing
C4	Disposal
D	Module D (Benefits and loads beyond the system boundary)
GWP total	Global Warming Potential–Total
GWP fossil	Global Warming Potential–Fossil
GWP biogenic	Global Warming Potential–Biogenic
GWP LULUC	Global Warming Potential–Land Use and Land Use Change
ODP	Ozone Depletion Potential
POCP	Photochemical Ozone Creation Potential
AP	Acidification Potential
EP freshwater	Eutrophication Potential–Freshwater
EP marine	Eutrophication Potential–Marine
EP terrestrial	Eutrophication Potential–Terrestrial
ADPE	Abiotic Depletion Potential–Elements
ADPF	Abiotic Depletion Potential–Fossil Fuels
WU	Water Use

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