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Posted Date: 27 February 2026

doi: 10.20944/preprints202602.1710.v1

Keywords: Building-Integrated Photovoltaics (BIPV); Ecodesign for Sustainable Products Regulation (ESPR); Multi-Criteria Decision Analysis (MCDA); circular economy; Digital Product Passport (DPP)

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*Article*

# Ecodesign Prioritization for BIPV Manufacturers Under ESPR Compliance: An LLM-Assisted Multi-Criteria Framework with Use Cases Application

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**Abstract**

This study develops a human-centered AI framework enabling rapid ecodesign prioritization for ESPR compliance while demonstrating Large Language Model (LLM) integration in sustainability strategy. Four-stage hybrid methodology combining LLM-assisted action identification (30 ESPR-aligned interventions) with Multi-Criteria Decision Analysis with Analytic Hierarchy Process (MCDA-AHP) is developed. Expert validation addressed LLM-driven interventions limitations with practitioners evaluating AI suggestions based on value chain context. The framework applied to two Italian BIPV SMEs demonstrated strategic differentiation based on Feasibility vs. Desirability vs. Affordability producing systematically different action portfolios within regulation-aligned aggregate structures. Sensitivity analysis showed 100% priority stability under ±10% AHP variations for priority 1, 3 and 4 actions and 82% for priority 2 actions, validating framework robustness. The framework's provide empirical evidence for augmentation-not-automation in AI-assisted strategic planning, contributing replicable methodology for responsible LLM integration across manufacturing sectors. Results demonstrate combining AI synthesis efficiency with human contextual judgment enables regulation-aligned, business-model-specific sustainability strategies.

**Keywords:** Building-Integrated Photovoltaics (BIPV); Ecodesign for Sustainable Products Regulation (ESPR); Multi-Criteria Decision Analysis (MCDA); circular economy; Digital Product Passport (DPP)

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## 1. Introduction

The European Union's ESPR 2024/1781 [1] establishes mandatory ecodesign requirements across product lifecycle stages, with construction products expected to face stringent requirements by 2026-2027 including Digital Product Passport (DPP) obligations. Building Integrated Photovoltaic (BIPV) systems [2] present unique circularity challenges due to multi-material complexity (glass, aluminum, silicon, polymeric sealants) and long service lives (20-30 years). While individual component recyclability has been documented as for photovoltaic module recycling achieving 85% recovery rates under WEEE Directive 2012/19/EU [3] and aluminum recycling rates exceeding 75% worldwide [4], the integrated BIPV system lacks comprehensive ecodesign prioritization frameworks addressing the full product lifecycle. Several established methodologies address environmental product assessment, each with specific scopes and limitations when applied to complex building-integrated systems. To present some examples, Eco-Indicator 99 [5] employs a damage-oriented approach focusing on chemical impact categories (human health, ecosystem quality, resources), providing single-score environmental indicators. However, its chemical-centric focus and European-specific characterization factors limit applicability to regulatory compliance-driven prioritization and

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technical feasibility assessment for building products with long service lives and multi-stakeholder supply chains. ReCiPe [6] extends impact assessment with midpoint and endpoint indicators across 18 categories, offering comprehensive environmental profiling. While scientifically robust for comparative lifecycle assessment, ReCiPe requires extensive inventory data and LCA expertise, creating barriers in particular for Small-Medium Enterprises (SMEs) lacking dedicated sustainability departments. Indeed, these methodologies do not inherently address regulatory compliance urgency or economic implementation constraints. Circularity Assessment framework [7], Material Circularity Indicator [8], Circular Transition Indicators [9] evaluate circularity performance through metrics like recycled content, product lifetime and end-of-life recovery. These frameworks excel at measuring circularity outcomes but provide limited guidance on which specific actions to prioritize given technical feasibility constraints, market readiness and capital availability, three critical factors for manufacturers facing ESPR compliance deadlines. Design for X (DfX) [10] methodologies (Design for Disassembly, Design for Recycling) offer qualitative checklists and best practices but lack quantitative prioritization mechanisms integrating regulatory urgency with company-specific capabilities. Their generic nature requires significant adaptation to sector-specific contexts like BIPV façade systems. These existing tools exhibit three critical gaps when applied to BIPV manufacturers navigating ESPR compliance: (i) regulatory urgency disconnect with environmental assessment tools quantify impacts, but do not prioritize actions based on mandatory compliance deadlines versus voluntary improvements; (ii) technical-economic feasibility integration with LCA-based tools assuming technical feasibility, whereas manufacturers face real-world constraints (supplier availability, capital budgets, production line compatibility) requiring explicit feasibility-affordability-desirability trade-off analysis; (iii) actionability for non-LCA experts with comprehensive tools demanding specialized expertise, while SME decision-makers (technical managers, CEOs, sustainability coordinators) require accessible frameworks translating regulatory requirements into concrete, prioritized action lists with implementation timelines.

Beyond these technical specific topics, the rapid adoption of Large Language Models (LLMs) by C-level executives – 65% regular usage for strategic analysis [11] and technical managers – creates opportunities for AI-augmented sustainability strategy under ESPR compliance pressures. LLMs excel at synthesizing regulatory requirements, benchmarking industry practices and suggesting preliminary action portfolios, accelerating early-stage ecodesign scoping before committing to resource-intensive working activities [12]. However, uncritical AI reliance risks strategic misalignment. LLMs lack access to company-specific contexts, supply chain constraints, competitive positioning, organizational capabilities, that determine which ecodesign actions are genuinely feasible, desirable and affordable. AI-generated sustainability strategies may be technically plausible yet operationally disconnected from business realities, potentially hallucinating technical claims [13] or recommending actions misaligned with regional regulatory contexts. Human-centric AI design [14] can address these risks by positioning LLMs as augmentation rather than automation. Indeed, AI generates candidate actions and suggests preliminary scores, while C-level executives and technical managers validate, correct and override suggestions through structured decision protocols. This approach combines AI's information synthesis efficiency with human strategic judgment, critical for early-stage prioritization where rapid scenario exploration precedes detailed analysis.

This study addresses these gaps by adapting and adopting a Multi-Criteria Decision Analysis (MCDA) framework specifically designed for BIPV manufacturers with three distinguishing features: (i) sector-specific action LLM generated libraries with ecodesign interventions aligned with ESPR Annex V categories and BIPV technical characteristics, reducing time-to-prioritization versus generic assessment tools; (ii) stakeholder-weighted criteria with company leadership (CEOs, technical directors) weighting feasibility-desirability-affordability criteria via Analytic Hierarchy Process (AHP), embedding strategic priorities directly into prioritization outcomes; (iii) regulatory compliance integration with explicit consideration of mandatory deadlines and market access requirements alongside environmental performance, reflecting real-world decision-making contexts. The MCDA-AHP framework prioritizes ecodesign interventions to inform strategic resource

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allocation under regulatory deadlines and budget constraints. The framework serves a distinct decision-support function from LCA-based tools: whereas LCA quantifies environmental impacts to inform product optimization, this LLM-MCDA-AHP framework aims at prioritizing strategic vision integration. This study validates the framework through application to two case studies: (1) a BIPV-IGU component manufacturer and (2) a curtain wall façade system integrating BIPV-IGU, demonstrating applicability across supply chain positions and product complexity levels, as well as the interoperability among actors which are in the same supply chain.

## 2. Materials and Methods

The following methodology has been adopted:

- **Multi-Criteria Decision Analysis framework.** The prioritization framework employs a Weighted Linear Combination (WLC) method, a standard MCDA approach applied as proof-of-concept for sustainability assessment and new product development [15–18]. Three evaluation criteria were selected based on the Feasibility-Desirability-Viability scorecard framework adapted from design thinking methodology [19]:
  - Feasibility (F): technical capability to implement with current manufacturing infrastructure and supply chain access.
  - Desirability (D): market demand strength and regulatory compliance urgency.
  - Affordability (A): economic accessibility considering capital investment and operational cost implications.

Scores represent expert judgment informed by company-specific operational knowledge rather than quantitative measurement, acknowledging this as a limitation requiring validation through implementation tracking. Technical feasibility assessments were grounded in peer-reviewed literature, industry standards and technology readiness reports. Market desirability indicators incorporated regulatory analysis and nZEB/ZEB/PEB requirements [20]. Economic affordability estimates were based on industry benchmarks for similar ecodesign implementations in building product manufacturing, acknowledging these as practitioner estimates rather than empirically validated cost data. Each criterion was assessed on a 5-point Likert scale (1=lowest, 5=highest) [21] as described in based in Table 1**Table 1.** and developed iteratively with case study participants to ensure scoring consistency and practical relevance to building product manufacturing contexts.

**Table 1.** Table for Likert score for ecodesign actions.

| Score | Feasibility | Desirability | Affordability |
|---|---|---|---|
| **5** | Implementable with existing infrastructure; suppliers readily available | Mandatory compliance requirement with <2 year deadline OR strong competitive advantage | ROI <2 years |
| **4** | Minor adaptation required; 1-2 suppliers available | Regulatory trend or customer preference shift; moderate competitive advantage | ROI 2-4 years |
| **3** | Moderate changes needed; limited supplier availability | Industry best practice; neutral competitive position | ROI 4-6 years |
| **2** | Significant technical challenges; supplier development required | Emerging trend; uncertain market uptake | ROI 6-10 years |
| **1** | Not currently feasible; R&D breakthrough needed | No clear market demand; speculative value | ROI >10 years or uncertain |

Criteria weights is determined through structured interviews with company leadership actors using AHP [22] pairwise comparison matrices with numbers 1,3,5,9 and 1/3, 1/5, 1/9 used to quantify the relative importance of different criteria: a score of "1" means criteria are of equal importance, while a score of "9" indicates the first criterion is extremely more important than the second and

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vicevera “1/9” indicates the first criterion is extremely less important than the second. Composite score (S) calculation is:

$$S = (F \times AHP\ \%) + (D \times AHP\ \%) + (A \times AHP\ \%), \quad (1)$$

where S represents the weighted prioritization score (maximum = 5.0).

To ensure logical coherence of pairwise comparison judgments, maximum eigenvalue of the pairwise comparison matrix ($\lambda max$), Consistency Index (CI) and Consistency Ratio (CR) were calculated for each company's AHP weighting matrix following Saaty's methodology [22,23]. The consistency ratio quantifies whether decision-makers' pairwise comparisons contain logical contradictions. Following Saaty's widely adopted threshold, CR < 0.10 (10%) indicates acceptable consistency, meaning pairwise comparisons do not contain significant logical contradictions that would invalidate the derived priority weights. CRs is analyzed to check the consistency of AHP for the use cases.

- **Ecodesign actions identification.** Ecodesign actions were systematically identified across 16 ESPR goal categories: “durability”, “reliability”, “reusability”, “upgradability”, “repairability”, “maintenance and refurbishment”, “presence of substances of concern”, “energy use and efficiency”, “water use and efficiency”, “resource use efficiency”, “recycled content”, “remanufacturability”, “recyclability”, “recoverability”, “carbon footprint” and “waste generation” [1]. Each action was mapped to specific lifecycle stages (Design, Manufacturing, Use, End-of-Life) following ISO 14040 lifecycle assessment principles [24]. Action identification followed a four-stage hybrid human-AI process integrating LLM capabilities with expert validation (authors and industrial partners): (1) AI-assisted literature review (2015-2024) with LLM-powered analysis using 16 ESPR goal categories and Claude 4.5 Sonnet, Anthropic [25], is adopted to scout peer-reviewed publications on BIPV circularity, building product ecodesign, and ESPR compliance strategies with references to documents and reports; (2) analysis of ESPR 2024/1781 Annex V requirements, cross-referenced with building product standards and nZEB/ZEB/PEB technical specifications, filtering to n=30 regulation-aligned actions with mapped lifecycle stages and desirability indicators (mandatory compliance deadlines, market access requirements); (3) n.5 BIPV industry practitioners (manufacturers, façade engineers, sustainability consultants) evaluated AI-generated action portfolio, validating technical feasibility against real-world supply chain constraints (supplier availability, production line compatibility, capital investment requirements), filtering the n=30 implementable actions with corrected affordability estimates based on practitioner experience rather than AI-suggested generic benchmarks; (4) case study companies checked action comprehensiveness, clarity and strategic relevance, finalizing 30 common ESPR actions (applicable across BIPV manufacturers) and sector-specific action templates (component-level vs. system-level interventions) with company-validated F-D-A scoring rubrics.
- **Priority classification.** Actions were classified using a hybrid approach combining MoSCoW prioritization (Must-Have, Should-Have, Could-Have, Won't-Have) [26] with urgency-importance matrix analysis [27]. MoSCoW was selected over alternative prioritization frameworks (e.g. Kano model, RICE scoring) due to its: (a) widespread adoption in project management [28]; (b) explicit time-horizon mapping (Must/Should/Could/Won't in 0-12/12-24/24-36/>36 months) aligning with ESPR compliance deadlines; (c) compatibility with regulatory mandate categorization (Must-Have = mandatory compliance, Could-Have = voluntary competitive advantage).

**Table 2.** Priority classification using MoSCoW and urgency-importance matrix analysis to target an ecodesign implementation timeline.

| Priority | Framework basis | Timeframe | Criteria |
|---|---|---|---|
| **P1** | MoSCoW "Must-Have" + High Urgency | 0-12 months | Score ≥4.0 OR regulatory deadline OR market access blocker |

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| | | | |
|---|---|---|---|
| **P2** | MoSCoW "Should-Have" | 12-24 months | Score 3.5-3.9 OR high competitive advantage |
| **P3** | MoSCoW "Could-Have" | 24-36 months | Score 3.0-3.4 OR strategic positioning value |
| **P4** | MoSCoW "Won't-Have (now)" | 36+ months | Score <3.0 OR requires significant R&D/investment |

- **Case study validation.** The methodology was applied to two manufacturers as proof-of-concept case studies demonstrating framework usability and output differentiation. Full validation, including tracking of implementation sequences, inter-rater reliability testing, and cross-case generalization, is acknowledged as a limitation requiring future research. Complementary case studies represent vertically integrated segments of the BIPV supply chain: BIPV component manufacturing with BIPV system integration to building construction (end customer), providing validation of framework applicability across supply chain positions with differentiated strategic priorities and technical complexities for ecodesign practices. The case studies are:
  - Case study 1 – BIPV-IGU manufacturer Glass to Power S.p.A. (G2P), Italy [29]. G2P is a technology-driven company specializing in the design and assembly of Building-Integrated Photovoltaic Insulating Glazing Units (BIPV-IGU). The company integrates monocrystalline silicon PV cells onto aluminum frames within insulating glass unit chambers, producing standardized and customized BIPV-IGU modules (typical dimensions 1000×1500 mm to 1500×3000 mm, power output 50-100 W/m²) for façade and skylight applications. Strategic positioning emphasizes product innovation (patent-pending PV mounting systems), architectural integration quality, and early-mover advantage in the Italian BIPV market. Primary customers include façade manufacturers like Gualini [30], architectural glazing contractors and design-build firms for commercial/institutional projects.

**Figure 1.** BIPV-IGU modules by Glass to Power. [31].

  - Case study 2 – BIPV Curtain Wall Façade System manufacturer Gualini S.r.l. (GUA), Italy [30]. Gualini is an established façade manufacturer producing unitized curtain wall systems for mid-to-high-rise commercial buildings across Europe and worldwide. The company specializes in custom-engineered aluminum-glass façade modules integrating building services (natural ventilation, solar shading, fire-rated compartmentation) with architectural aesthetics. Gualini's BIPV façade integrates G2P's BIPV-IGU modules (or competitor

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equivalents) into unitized façade frames with pre-wired electrical conduits, junction boxes and weather sealing. The company sources aluminum profiles (thermally broken extrusions), glass (via G2P or direct procurement for spandrel/vision areas), BIPV-IGU modules (G2P, other suppliers), electrical components (conduits, cable glands, junction boxes) and weatherproofing materials (EPDM gaskets, structural silicones) from diversified supply networks.

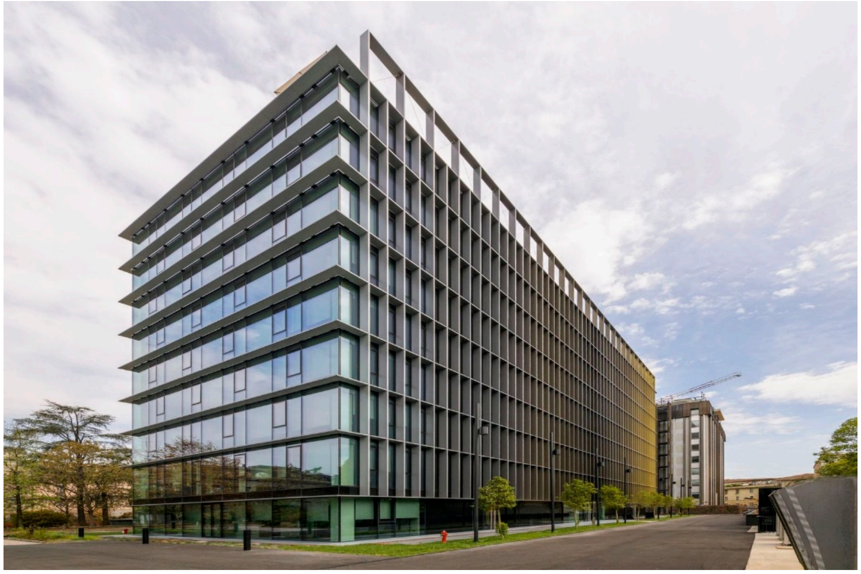

**Figure 2.** Bassi Business Park curtain wall façade by Gualini. [30].

- **Sensitivity analysis.** To assess the robustness of prioritization outcomes to AHP weight variations, sensitivity analysis was conducted following standard MCDA practice [32]. Each criterion weight was varied by ±10% from its baseline value, with compensatory adjustments to other criteria maintaining weight sum = 100%. Six sensitivity scenarios were tested per company (±10% variation for each of the three criteria F-D-A), recalculating composite scores (S) and priority classifications (P1-P4) for all actions under each scenario. Priority stability was quantified as the percentage of actions maintaining their baseline priority classification across all seven scenarios (baseline and 6 variations). Actions shifting priority classification in ≥3 scenarios were flagged as "boundary-sensitive," indicating proximity to priority thresholds (S = 4.0, 3.5, or 3.0) where small weight changes materially affect implementation sequencing. The ±10% variation magnitude was selected to represent plausible strategic priority shifts while remaining within reasonable bounds of the original AHP judgment. Larger variations (>20%) would question the validity of the original AHP exercise itself.

## 3. Results

### *3.1. AHP Weighting Profiles and Strategic Vision of Industrial Decision Makers*

The application and validation stage involved two industrial BIPV actors occupying different positions in the value chain: Glass to Power and Gualini. For each company, an AHP analysis was conducted with key decision makers to define the relative strategic importance of feasibility, desirability and affordability through pairwise comparison matrices with a scoring relied on single-rate assessment (CEO for G2P and Commercial director for Gualini); this single evaluation could introduce a potential individual bias, but considered a minor shortcoming for framework application validation. The results, validated for logical consistency, show markedly different weighting profiles (Table 3).

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**Table 3**. AHP pairwise comparison results and consistency validation.

| Company | F-weight | D-weight | A-weight | λmax | CI | CR | Consistency Status |
|---|---|---|---|---|---|---|---|
| **G2P** | 15.6% | 65.9% | 18.5% | 3.029 | 0.0145 | 2.51% | Excellent |
| **GUA** | 10.5% | 25.8% | 63.7% | 3.037 | 0.0185 | 3.19% | Excellent |

For G2P AHP profile, desirability was weighted at 65.9%, significantly higher than Affordability (18.5%) and Feasibility (15.6%), with CR = 2.51% confirming excellent logical consistency. This profile reflects G2P's strategic positioning as a technology-driven manufacturer introducing a relatively novel BIPV-IGU product to the market, where market acceptance, regulatory alignment, and value proposition communication are critical for business success. The pairwise comparisons reveal that G2P's CEO judged Desirability approximately 5 times more important than Feasibility when prioritizing ecodesign actions, a rational strategic orientation for an innovation-focused company where customer confidence in novel building products determines market penetration success and the low CR (2.51%) validates that these strategic judgments were internally consistent addressing actions enabling regulatory compliance, warranty extension for customer assurance and market-facing environmental credentials were systematically prioritized over technically complex but less market-visible interventions. For Gualini AHP profile, Affordability emerged as the dominant criterion with 63.7%, substantially higher than Desirability (25.8%) and Feasibility (10.5%), with CR = 3.19% confirming excellent consistency. This reflects Gualini's position within a consolidated façade market, where cost-efficiency, competitive pricing and integration within existing production and procurement structures are decisive factors for winning tender-based project contracts. The pairwise comparisons indicate that Gualini's leadership judged Affordability 5 times more important than Feasibility and 3 times more important than Desirability, reflecting the economic reality of façade procurement where projects are awarded based on ±5-10% price differentiation in competitive bidding. The low CR (3.19%) validates the coherence of this cost-oriented strategic vision: ecodesign actions delivering measurable cost savings will be systematically elevated in priority relative to actions with primarily regulatory or reputational value.

Both companies' CR values well below 5% (versus the 10% acceptability threshold) and indicate that decision-makers articulated clear, internally coherent strategic visions through the AHP process. This validates that the resulting priority weights genuinely reflect organizational strategic orientations rather than arbitrary or inconsistent judgments.

### *3.2. Ecodesign Action Portfolios and Priority Distribution*

For G2P, 42 ecodesign actions were identified and evaluated (Table A1 in Appendix A): 30 common ESPR General actions (C1-C30) applicable across BIPV manufacturers, plus 11 system-specific actions (G2P1-G2P11) addressing IGU component-level circularity (aluminum frame design, glass recycling partnerships, PV cell integration, IGU cavity management). For Gualini, 40 ecodesign actions were evaluated (Table A2 in Appendix A): 30 common ESPR General actions (C1-C30) with scored F-D-A values reflecting system-level complexity, plus 10 system-specific actions (GUA1-GUA10) addressing façade assembly logistics, electrical integration, service business models and supply chain coordination with G2P. The priority distribution across both companies demonstrates clear differentiation in implementation urgency driven by AHP weighting.

**Table 4.** Priority distribution for Glass to Power and Gualini ecodesign action portfolios showing implementation timeframes.

| Priority | Timeframe | G2P actions (n) | G2P percentage | GUA actions (n) | GUA percentage |
|---|---|---|---|---|---|
| **P1** | 0-12 months | 15 | 36.6% | 13 | 32.5% |
| **P2** | 12-24 months | 7 | 17.1% | 11 | 27.5% |

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| | | | | | |
|---|---|---|---|---|---|
| **P3** | 24-36 months | 14 | 34.1% | 13 | 32.5% |
| **P4** | 36+ months | 5 | 12.2% | 3 | 7.5% |

Both companies demonstrate a frontloaded implementation strategy with >32% of actions classified as P1 (0-12 months), reflecting urgent regulatory compliance needs (DPP implementation, EPD certification, SVHC documentation) and market access requirements (CE marking, warranty declarations). The relatively low P4 percentage (7.5-12.2%) indicates that most identified actions are considered implementable within 3-year horizon given current technical and economic constraints.

Analysis of P1 actions across ESPR Annex V goal categories reveals consistent prioritization patterns reflecting regulatory urgency and market imperatives for BIPV manufacturers:

**Table 5.** Distribution of P1 priority actions across ESPR Annex V goal categories for G2P and GUA.

| ESPR goal category | G2P P1 actions | GUA P1 actions | Common pattern |
|---|---|---|---|
| **Carbon footprint** | 3 (C1, C2, G2P1) | 3 (C1, C3, GUA1) | Mandatory PCF for DPP; transport optimization critical for Gualini due to large module shipments |
| **Durability** | 2 (C5, G2P3) | | Warranty extension drives market competitiveness |
| **Energy** | 2 (C6, G2P4) | | G2P prioritizes PV efficiency |
| **Maintenance** | 2 (C7, G2P5) | 1 (C7) | Inspectability essential for both; differentiated by component vs façade accessibility |
| **Reliability** | 2 (C15, C16) | 1 (C16) | EPD certification for G2P and CE marking is mandatory compliance action for both |
| **Repairability** | 3 (C17, C18, C19) | 4 (C18, C19, GUA9, GUA10) | DPP implementation deadline 2026-2027 drives P1 urgency for G2P; Gualini adds snap-fit conduit (GUA9) for service business model |
| **Resource** | | 1 (C22) | Optimization of large amount of materials for production |
| **Reusability** | | 1 (C23) | Standardized components for stock optimization |
| **Substances** | 1 (C24) | 2 (C24, C25) | VOC-free materials baseline; Gualini elevates SVHC documentation (C25) to P1 due to system-level complexity |

Repairability emerges as the most critical ESPR goal category with 3-4 P1 actions per company, requiring repair documentation, component accessibility and spare parts availability. Reliability follows closely with EPD and CE marking requirements representing non-negotiable market access conditions. Carbon footprint actions cluster in P1-P2 due to increasing customer demand for verified environmental data and anticipated regulatory requirements for embodied carbon declarations in public procurement. Notably, Recyclability and Remanufacturability actions predominantly fall in P3-P4 priorities (e.g. G2P6 butyl sealant replacement, G2P10 IGU cavity refilling), indicating that while technically feasible, these advanced circular economy interventions face economic and supply chain readiness constraints requiring longer development timelines.

### *3.3. Comparative Analysis: AHP Influence on Common Action Prioritization*

The 30 common ESPR General actions (C1-C30) were scored independently by G2P and Gualini, resulting in differentiated F-D-A assessments and consequently divergent priority classifications. Table 6 presents actions with variance results demonstrating AHP weighting impact.

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**Table 6.** Selected common actions demonstrating AHP-driven prioritization variation between G2P and Gualini.

| ID | Action Description | G2P Score | GUA Score | Δ Score | Δ Priority |
|---|---|---|---|---|---|
| **C1** | Develop verified Carbon footprint (PCF) for DPP | 4,66 | 4,26 | 0,39 | Same |
| **C2** | Source low-carbon/local aluminium (<4 kg $CO_2e$/kg) from suppliers | 4,63 | 3,73 | 0,89 | ↑1 level |
| **C3** | Optimize transport mode selection (rail/truck) based on distance | 2,66 | 4,63 | -1,98 | ↓3 level |
| **C4** | Source from suppliers with renewable energy credentials | 3,66 | 3,26 | 0,39 | ↑1 level |
| **C5** | Declare and extend warranty period (10-15 years) | 4,47 | 3,63 | 0,84 | ↑1 level |
| **C6** | Source low-embodied energy materials from supply chain | 4,31 | 3,37 | 0,94 | ↑2 level |
| **C7** | Design for inspectability at critical points | 4,66 | 4,26 | 0,39 | Same |
| **C8** | Integrate IoT remote monitoring system | 3,16 | 3,11 | 0,05 | Same |
| **C9** | Document disassembly sequence in DPP | 3,34 | 3,74 | -0,39 | ↓1 level |
| **C10** | Partner with glass recyclers for closed-loop recovery | 2,81 | 2,37 | 0,45 | Same |
| **C11** | Establish WEEE-compliant take-back program | 3,31 | 2,52 | 0,79 | ↑1 level |
| **C12** | Create material passport for DPP (materials inventory) | 3,34 | 3,74 | -0,39 | ↓1 level |
| **C13** | Design dry fastening connections, eliminate permanent adhesives | 3,00 | 3,00 | 0,00 | Same |
| **C14** | Source high recycled aluminium (≥75%) from suppliers | 3,81 | 3,37 | 0,45 | ↑1 level |
| **C15** | Obtain EPD certification (EN 15804+A2) for product | 4,63 | 3,63 | 1,00 | ↑1 level |
| **C16** | Implement quality control labeling (CE marking per CPR) | 4,81 | 4,37 | 0,45 | Same |
| **C17** | Implement DPP system per ESPR Art. 9-13 | 4,47 | 3,52 | 0,95 | ↑1 level |
| **C18** | Publish repair/maintenance documentation via DPP | 4,34 | 4,74 | -0,39 | Same |
| **C19** | Design accessible junction boxes/electrical connections | 4,19 | 4,63 | -0,45 | Same |
| **C20** | Provide 3D models/digital twins for replaceable components | 2,53 | 3,37 | -0,84 | ↓1 level |
| **C21** | Optimize component-to-frame ratio for material efficiency | 3,34 | 3,74 | -0,39 | ↓1 level |
| **C22** | Implement nesting optimization, reduce scrap during cutting/machining | 3,34 | 4,11 | -0,76 | ↓2 level |
| **C23** | Standardize components across product variants (modular design) | 3,50 | 4,11 | -0,60 | ↓1 level |
| **C24** | Source materials with VOC-free/low-VOC certifications from suppliers | 4,16 | 4,37 | -0,21 | Same |
| **C25** | Document SVHC substances in DPP per ESPR Art. 7(5) | 3,34 | 4,00 | -0,66 | ↓2 level |
| **C26** | Design modular electrical connections for future component upgrades | 3,66 | 3,26 | 0,39 | ↑1 level |
| **C27** | Implement scrap recovery systems (Al to remelting, glass cullet return) | 3,34 | 3,74 | -0,39 | ↓1 level |

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| | | | | | |
|---|---|---|---|---|---|
| **C28** | Zero-waste-to-landfill target for manufacturing operations | 3,00 | 3,00 | 0,00 | Same |
| **C29** | Design for selective demolition and component separation | 3,00 | 3,00 | 0,00 | Same |
| **C30** | Source ASI-certified aluminium (water stewardship criteria) | 3,50 | 3,85 | -0,34 | Same |

The most divergence occurs in C3 (transport optimization), where Gualini's Affordability-dominant weighting (63%) combined with high affordability scoring (A=5 for rail transport cost savings) elevates this action from P4 to P1 priority. This also depends on the dimensions, complexities and location of the supply chain provision: Gualini currently has Europe and worldwide project convenient for rail transport, while G2P has smaller projects at national scale that are difficult to optimize for trail transportation. Conversely, G2P's Desirability-focused profile (66%) deprioritizes logistics efficiency in favor of market-facing actions like warranty extension (C5). C22 (nesting optimization) illustrates how identical technical feasibility (both F=4) translates to different priorities based on business model: Gualini's manufacturing with high material volumes benefits significantly from scrap reduction (A=4 scores highly under 63% Affordability weighting), whereas G2P's lower-volume component assembly renders this action less strategically urgent (P3). C25 (SVHC documentation) reveals complexity-driven differentiation: Gualini must aggregate SVHC data across façade aluminum profiles, structural sealants, electrical conduits and embedded G2P components, creating higher compliance burden (D=4) that pushes this action to P1 under Desirability's 26% weight. G2P's component-level SVHC tracking remains P3 given simpler material inventory. These examples confirm that the AHP weighting mechanism translates strategic business vision into operationally differentiated action prioritization, rather than producing generic sustainability rankings.

### *3.4. System-Specific Actions: Supply Chain Differentiation*

The 11 G2P-specific actions (G2P1-G2P11) and 10 Gualini-specific actions (GUA1-GUA10) reveal distinct circular economy strategies arising from value chain positioning. This is particularly relevant because they move from common ESPR compliant interventions, to system-oriented, demonstrating how also for these peculiar actions, a prioritization can support a strategic roadmap. The Table 7 shows the number of system-specific priorities and common actions for the use cases.

**Table 7.** Priority distribution: "System-specific" vs. "ESPR General" actions.

| Company | Priority | System-specific (n) | System-specific percentage | ESPR General (n) | ESPR General percentage |
|---|---|---|---|---|---|
| **G2P** | P1 | 4 | 36.4% | 11 | 36.7% |
| | P2 | 2 | 18.2% | 5 | 16.7% |
| | P3 | 3 | 27.3% | 11 | 36.7% |
| | P4 | 2 | 18.2% | 3 | 10.0% |
| **GUA** | P1 | 3 | 30.0% | 10 | 33.3% |
| | P2 | 2 | 20.0% | 9 | 30.0% |
| | P3 | 4 | 40.0% | 9 | 30.0% |
| | P4 | 1 | 10.0% | 2 | 6.7% |

The MCDA-AHP framework demonstrated robust applicability to both LLM-generated ESPR General actions and company-specific contextual interventions. For G2P, system-specific actions (n=11) exhibited nearly identical priority distribution to ESPR General actions (n=30) 36.4% vs. 36.7% classified as P1 (Must-Have), confirming consistent business-oriented evaluation regardless of action origin. GUALINI demonstrated comparable patterns: system-specific actions (n=10) showed 30.0% vs. 33.3% P1 classification relative to ESPR General actions. This convergence validates that strategic

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priorities, not action source, determine implementation urgency. Both companies allocate ~25% of total P1 actions to system-specific interventions (G2P: 4 of 15 P1 actions; GUALINI: 3 of 13 P1 actions), demonstrating the framework balances regulatory compliance with competitive differentiation. The clustering of Gualini's P1 system-specific actions around electrical repairability (GUA9, GUA10) reflects the strategic importance of non-destructive electrical troubleshooting and component replacement for façade suppliers, opening also to differentiation service business model due to the fact that these design interventions create long-term revenue streams through maintenance agreements, a consideration absent from G2P's component supply business model. Conversely, G2P's focus on product performance (G2P3 climate protection, G2P4 PV efficiency) and renewable energy transitions (G2P1) aligns with market positioning as a technology innovator where environmental credentials and electrical yield directly influence customer purchasing decisions. Notably, both companies prioritize renewable energy transitions for their manufacturing facilities (G2P1, GUA1) as P1 actions, but through divergent strategic rationales: G2P emphasizes Desirability (market differentiation, D=4), whereas Gualini emphasizes Affordability (energy cost reduction, A=5) – illustrating how identical interventions serve different strategic objectives captured by AHP weighting.

### *3.5. Sensitivity Analysis: Priority Robustness to AHP Weight Variations*

Sensitivity analysis across six weight variation scenarios (±10% per criterion) demonstrated high overall priority stability for both companies: G2P has 38/41 actions (92.7%) maintained baseline priority classification across all scenarios; GUALINI has 39/40 actions (97.5%) maintained baseline priority classification across all scenarios (Table 8).

**Table 8.** Priority stability by baseline priority level.

| Company | Baseline priority | # Actions | # Stable | % Stable |
|---|---|---|---|---|
| **G2P** | P1 | 15 | 15 | 100% |
| | P2 | 7 | 4 | 57% |
| | P3 | 14 | 14 | 100% |
| | P4 | 5 | 5 | 100% |
| **GUA** | P1 | 13 | 13 | 100% |
| | P2 | 11 | 10 | 91% |
| | P3 | 13 | 13 | 100% |
| | P4 | 3 | 3 | 100% |

Based on sensitivity analysis four actions (G2P: C23, G2P11, C30; GUALINI: C17) exhibited priority classification shifts in <4 sensitivity scenarios. These actions have a value in baseline scenario close to 3.50 (G2P 3.58, GUA 3.52) and consequently are boundary-sensitive actions. Generally, the high stability rates validate that prioritization outcomes are robust to reasonable strategic priority shifts. Actions classified as P1 ($S \geq 4.0$) are stable (G2P 100%, GUA 100%), confirming that these represent non-negotiable priorities regardless of modest weight adjustments.

Beyond this classification, chi-square test of independence [33] confirmed no statistically significant difference between G2P and GUA priority distributions for common actions ($\chi^2(3) = 1.590$, $p = 0.66$), validating convergent ESPR compliance responses classified as P1 (G2P 36.7%, GUA 33.3%). The low $\chi^2$ value demonstrates the framework produces regulation-aligned prioritization appropriate for compliance contexts [34], where institutional coercive pressures create isomorphic organizational responses to mandatory requirements. Strategic differentiation manifests at the action-composition level rather than aggregate distribution patterns [35], G2P's P1 portfolio emphasizes market credentials (C15 EPD certification, C17 DPP implementation per ESPR Art. 9-13), while GUA's emphasizes cost-optimization (C3 transport logistics, C22 nesting efficiency), reflecting respective AHP weighting priorities (Desirability 66% vs. Affordability 63%.

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## 4. Discussion

The framework's applicability demonstrates that LLM pre-structured action libraries with the 30 common ESPR General actions (C1-C30) and 11/10 customized system-specific interventions provide a ready-made checklist aligned with regulatory requirements, eliminating the need for manufacturers to independently interpret ESPR Annex V categories into concrete interventions. In this perspective, the adoption of Likert-scale accessibility with the 5-point F-D-A scoring system proved accessible to C-level and technical managers able to assign scores based on operational knowledge (supplier capabilities, production line constraints, market feedback). This guarantees a transparent prioritization through the AHP weighting process, making explicit how strategic vision (market positioning, cost competitiveness, regulatory urgency) translates into action prioritization, but it lacks quantitative rigor for boundary-sensitive actions (4.9% of portfolio). This is particular relevant moving beyond the utilization of LLM-generated intervention without specific business model and system-oriented adoption. However, the priority stability under ±10% AHP weight variations validates the framework's strategic robustness while enabling adaptive recalibration. The MCDA-AHP approach's sensitivity to weight variations represents a deliberate feature: as strategic priorities evolve (e.g. market conditions shift, regulatory deadlines approach, competitive dynamics change), companies can re-run the AHP weighting exercise and systematically recalibrate action priorities.

The contrasting AHP profiles between G2P (Desirability 66%) and Gualini (Affordability 63%) demonstrate the framework's capacity to embed company-specific strategic vision into ecodesign prioritization, a capability absent from standardized assessment tools. This differentiation reflects fundamentally different competitive dynamics. G2P's Desirability-driven profile aligns with market realities for emerging building-integrated PV technologies, where customer adoption barriers include uncertainty about performance reliability, aesthetic integration and long-term value proposition. By weighting Desirability at 66%, G2P's prioritization elevates actions that build market confidence: warranty extension (C5, S=4.47), EPD certification (C15, S=4.63), and DPP transparency (C17, S=4.47). These regulatory compliance and communication-focused interventions directly address specifier concerns in architectural projects where BIPV-IGU represents a novel, higher-risk glazing choice compared to conventional curtain walls. Gualini's Affordability-driven profile reflects the competitive intensity of the unitized façade market, where project acquisition depends on cost competitiveness. The 63% Affordability weighting prioritizes cost-reduction actions: transport optimization (C3, S=4.63 via rail savings), nesting efficiency (C22, S=4.11 for scrap reduction), and off-site renewable energy (GUA1, S=4.74 for long-term energy cost savings). This profile acknowledges that while environmental performance increasingly influences façade procurement decisions, price remains the decisive factor in competitive bidding, a reality often overlooked in sustainability frameworks emphasizing only environmental outcomes. The framework's sensitivity to these strategic contexts is evidenced by the priority comparison for common actions: C22 (nesting optimization) shifts from P3 for G2P to P1 for Gualini despite identical technical feasibility (both F=4), solely due to divergent Affordability weighting. This demonstrates that effective ecodesign prioritization for building products cannot apply uniform sustainability hierarchies but must account for sector-specific market structures and business model differentiation. This strategic alignment capability positions the MCDA-AHP framework as a vision creation tool for business decision-makers, translating abstract sustainability commitments (e.g. "transition to circular economy") into operationally coherent action sequences reflecting competitive positioning. The AHP weighting mechanism operationalizes the concept that circular economy transitions must align with competitive strategy to achieve industry-wide adoption [36]. Despite the identical ESPR requirements yield, divergent implementation pathways are filtered through business model differentiation (G2P's Desirability focus vs. Gualini's Affordability focus). This contributes to sustainability-as-strategy literature [37] by showing how AHP weights formalize strategic vision, making explicit the implicit trade-offs executives navigate when allocating sustainability resources. For instance, G2P's CR of 2.51% confirms that when the CEO judged Desirability 5× more important than Feasibility, this

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comparison was mathematically consistent creating a logically coherent prioritization hierarchy. The absence of circular contradictions (where A > D, D > F, but F > A) demonstrates that the AHP weighting process successfully translated strategic priorities into quantified, operationally usable criteria weights. These profiles confirm that the AHP component of the framework effectively captures company-specific strategic vision, translating it into differentiated prioritization logics rather than imposing uniform sustainability hierarchies. The validation results support the framework's core claim: that effective ecodesign prioritization requires embedding business model differentiation into the decision-support methodology through stakeholder-weighted criteria. Indeed, if on the one side, the clustering of P1 actions around Repairability (3-4 actions) and Reliability (EPD, CE marking) reflects coercive isomorphism [34] with mandatory compliance driving organizational change, on the other, the differentiated P1 distributions within the same regulatory context suggest that strategic interpretation mediates normative coercive pressures. The MCDA-AHP framework operationalizes this mediation through AHP weights, showing how organizational strategy filters regulatory demands into heterogeneous responses.

The explicit cross-referencing structure between G2P and Gualini action matrices reveals a critical but under-addressed dimension of BIPV ecodesign: circularity cannot be achieved by individual actors but requires coordinated interventions across supply chain positions. Examples are C10-GUA4 interaction, or C4 or C12 for material passport aggregation. These patterns suggest that while the MCDA-AHP framework effectively prioritizes actions within company boundaries, BIPV sector decarbonization requires supplementary coordination tools, potentially including shared P1 priority lists for pre-competitive interventions (e.g. DPP data standards, recycling infrastructure development, supplier sustainability requirements) agreed upon through industry associations. The framework's transparency in identifying interdependencies creates a foundation for such coordination by making explicit where individual priorities generate collective implementation gaps.

However, the framework's accessibility entails inherent limitations. F-D-A scores represent expert judgment rather than empirical measurement, introducing subjectivity particularly for affordability estimates. The study acknowledges this as a methodological trade-off: rapid prioritization for early-stage strategy formulation versus quantitative precision for detailed implementation planning. Future integration of Life Cycle Costing [38,39] would transform subjective affordability assessments into empirical Net Present Value (NPV) calculations with confidence intervals, or TOPSIS methodology [40] could resolve prioritization ambiguities for actions with conflicting F-D-A profiles. This two-stage approach, qualitative MCDA for portfolio scoping (days), quantitative LCC-TOPSIS for boundary validation (weeks/months) could balance rapid strategic planning with investment-grade analytical rigor, while refining high-priority action rankings based on quantitative data. Additionally, the weighted linear combination method employed assumes criteria independence (Feasibility, Desirability, Affordability do not interact) and full compensability (high score on one criterion can offset low score on another). These assumptions may not hold in practice. For example, an action scoring F=5, D=5, A=1 (highly feasible and desirable but unaffordable) might receive score $S = (5\times0.16) + (5\times0.66) + (1\times0.19) = 4.29$ (P1 priority for G2P), despite capital budget constraints making implementation impossible. This suggests that criteria as "Affordability" should function as a threshold rather than a compensatory criterion, actions with A<2 should be automatically excluded from P1-P2 regardless of F-D scores. Future methodological refinement should test hybrid approaches combining threshold constraints with WLC aggregation.

## 5. Conclusions

The validation results with Glass to Power and Gualini demonstrate that the proposed framework addresses critical gaps in existing ecodesign assessment methodologies when applied to building product manufacturers facing ESPR compliance deadlines. The framework demonstrates the capacity to systematically evaluate all 41 LLM-identified interventions for G2P and 40 for GUALINI validating the hybrid human-AI methodology: LLMs generate comprehensive portfolios spanning regulatory and operational domains, while human expert validation (AHP weighting, F-D-

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A scoring) ensures strategic alignment. This positions the framework as technology-neutral strategic tool integrating ESPR compliance obligations with proprietary innovations through unified business-model-centric prioritization, rather than treating circular economy regulations as separate from competitive strategy. This study developed and applied a MCDA framework specifically designed to support Building-Integrated Photovoltaic manufacturers in prioritizing ecodesign actions aligned with the European Ecodesign for Sustainable Products Regulation (ESPR 2024/1781). Through application to two industrial case studies, a BIPV-IGU component manufacturer (Glass to Power) and a curtain wall façade system integrator (Gualini). The research demonstrates that strategic business vision, captured through analytic hierarchy process weighting, fundamentally shapes ecodesign implementation priorities even when companies face identical regulatory requirements.

The framework addresses critical gaps in existing ecodesign assessment methodologies by providing rapid, actionable prioritization for manufacturers lacking resources for comprehensive LCA or circularity assessment. While simplified LCA tools (e.g. One Click LCA [41],Tally [42]) have improved accessibility for non-experts, they still require product-level data (material quantities, supplier locations, transport modes) often unavailable at early design stages, time investment, and environmental impact interpretation skills to translate results business decisions. The MCDA-AHP framework complements these tools by enabling rapid strategic prioritization (4-6 hours) using operational knowledge (supplier availability, production constraints) accessible to CEOs/technical managers, without requiring environmental expertise. The trade-off is precision (qualitative F-D-A scores) versus speed (workshop-based prioritization). For manufacturers in early-stage sustainability strategy development, this vision alignment may prove more valuable than comprehensive environmental quantification, enabling consensus-building among leadership on resource allocation priorities. The framework's originality lies in its dual function as both a decision-support tool and a vision creation instrument for business decision-makers. Unlike assessment methodologies that quantify environmental impacts but leave strategic prioritization to users, the MCDA-AHP approach explicitly operationalizes strategic vision through weighted criteria, translating abstract sustainability commitments into concrete action sequences coherent with competitive positioning. This vision creation function proves particularly valuable for BIPV manufacturers in early-stage sustainability strategy development, where defining "what to do first" often represents a greater barrier than understanding "what should eventually be done." The framework support the challenge of this prioritization paralysis by: (i) making trade-offs transparent with AHP weighting forcing explicit articulation of whether market positioning (Desirability), technical capability (Feasibility), or cost competitiveness (Affordability) should drive decision-making when these criteria conflict; (ii) legitimizing differentiated pathways by demonstrating company-driven actions differentiation while complying with the same regulations, the framework validates that multiple sustainability strategies can be effective, reducing pressure for uniform industry approaches that may not align with individual business models; (iii) enabling resource-constrained action with the P1-P4 classification with timeframes allows SMEs to sequence investments strategically (focusing capital on 0-12 month priorities) rather than attempting simultaneous implementation of all ESPR requirements, which would exceed financial and organizational capacity. For BIPV manufacturers navigating the transition from traditional building products to circular economy-aligned systems, this strategic coherence between sustainability commitments and business operations may prove as valuable as quantitative environmental performance measurement, particularly in securing leadership buy-in and organizational alignment for ecodesign implementation.

Beyond these limitations, the framework's demonstrated ability to differentiate priorities based on company’s strategic context while maintaining methodological consistency suggests scalability potential, provided that action libraries are co-developed with target user groups to ensure sector relevance. In particular, while validating with two manufacturers, the framework's architecture suggests broader applicability across value chain positions:

BIPV upstream actors (PV cell manufacturers, glass producers). The common action library (C1-C30) addresses generic ESPR requirements applicable to any building product manufacturer (carbon

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footprinting, EPD certification, recycled content, SVHC documentation). Component suppliers would retain these actions while substituting system-specific portfolios (e.g. PV cell manufacturers might include "transition to silver-free metallization" analogous to G2P's silver-to-copper busbar action from, or glass producers might prioritize "increase cullet content to 80%" analogous to G2P8). The AHP weighting would reflect supplier-specific strategic contexts.

BIPV downstream actors (installation contractors, building owners). While the current framework targets manufacturers, the methodological structure (stakeholder-weighted MCDA, action libraries, MoSCoW prioritization) could adapt to end-user contexts. Installation contractors might prioritize actions like "develop DPP-compliant installation documentation" (analogous to C9 disassembly documentation) or "establish maintenance service contracts" (analogous to GUA3), weighted toward Feasibility if labor skills are the primary constraint. Building owners engaging in deep renovations might prioritize "specify BIPV-IGU with material passports for future recoverability" (analogous to C12), with AHP weighting reflecting total cost of ownership (Affordability) versus ESG reporting requirements (Desirability).

Cross-sector applicability. The framework's sector-agnostic methodological core (MCDA-AHP, MoSCoW, lifecycle stage mapping) suggests transferability to other multi-material building products other than BIPV facing ESPR compliance, such as insulated façade panels, smart windows, or modular building systems. Adaptation would require developing sector-specific action libraries (e.g. for insulated panels: "replace XPS foam with bio-based insulation") while retaining the common ESPR actions applicable across building products. The key transferability criterion is multi-stakeholder supply chains with differentiated strategic priorities, a characteristic shared across construction product categories.

Despite this application and validation, the framework's validation remains limited to two manufacturers within a single geographic market (Italy) and technological category (BIPV-IGU and BIPV façade). Generalization requires testing across:

Company size variations. Both G2P and Gualini are SMEs and applicability to large multinational façade manufacturers with dedicated sustainability departments remains unvalidated. Larger organizations might find the framework's simplicity insufficient, requiring integration with more sophisticated decision-support systems.

Multi-stakeholder scoring validation. Replicating the framework with 3-5 additional BIPV manufacturers, employing multi-rater scoring (C-level and company decision makers as CEO, technical director, sustainability manager) with inter-rater reliability testing. This would assess generalizability and scoring robustness.

Market maturity contexts. Both companies operate in European markets with established ESPR regulatory frameworks. Applicability to regions with less stringent environmental regulations (where Desirability for compliance may be lower) or more mature BIPV markets (where Affordability pressures might differ) requires empirical validation.

Framework validation under implementation. Implementation tracking with companies (e.g. G2P and Gualini), requires to be checked with recurrent interviews documenting which P1-P2 actions were implemented, in what sequence, with what barriers encountered. This would validate predictive accuracy and refine scoring criteria based on implementation realities also in the vision of MCDA-LCA integration pilot where high-priority actions (P1-P2 from framework) undergo targeted LCA quantification (carbon footprint, embodied energy) to validate whether qualitatively prioritized actions also deliver quantitatively significant environmental benefits. This would bridge strategic prioritization with impact measurement.

This research demonstrates that effective ecodesign prioritization for building products requires more than environmental impact quantification, it necessitates strategic business vision integration to ensure sustainability initiatives align with competitive realities and organizational capabilities. The MCDA-AHP framework provides BIPV manufacturers for translating ESPR regulatory requirements into actionable implementation roadmaps differentiated by business model, while revealing supply chain interdependencies requiring collaborative intervention though a framework which enables

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rapid ESPR prioritization without LCA expertise. The application of this model could open new services model to transform ESPR compliance uncertainty into actionable roadmaps within 1 working day through AI-assisted workshops. Service combines LLM-powered action identification with facilitated AHP sessions capturing executive strategic vision (Feasibility-Desirability-Affordability weighting). Technical consultants validate AI-suggested scores using supply chain expertise, generating regulation-aligned P1-P4 priorities. The framework's transparency (visible calculations, clear classification logic) builds client capability, participants learn prioritization methodology applicable to future reviews, reducing dependency for routine updates while creating opportunities for higher-value services (detailed LCA for P1 actions, supplier engagement, DPP implementation). For consultancies, this could represent strategic repositioning from labor-intensive analysis providers to facilitators of AI-augmented executive decision-making, where consultant value derives from strategic framing, stakeholder alignment, and technical validation rather than raw information gathering – activities less susceptible to AI commoditization. The MCDA-AHP framework exemplifies the (1) integration of LLMs for rapidly generate action portfolios from ESPR Annex V requirements and company documents, with (2) C-level leadership defining strategic priorities via AHP weighting (capturing business model contexts AI cannot infer) and (3) technical managers overriding AI-suggested Feasibility-Desirability-Affordability scores using supply chain knowledge. The result is that (4) framework generates prioritized roadmaps (P1-P4 classifications, implementation timelines) with transparent methodology enabling trust calibration. This design enables manufacturers to leverage daily-use AI assistants (ChatGPT, Claude, Copilot) for compliance planning without sacrificing strategic alignment, positioning AI as a strategy acceleration tool supporting human decision-making rather than replacing it.

As the European construction sector navigates the transition towards circular economy systems mandated by ESPR 2024/1781, methodologies supporting manufacturers in defining what to do first can contribute to that methodological foundation, demonstrating that strategic coherence, supply chain coordination and regulatory compliance urgency are co-equal considerations alongside environmental performance in enabling sustainable building product innovation. The LLM-MCDA-AHP framework's validation confirms that diverse pathways toward circularity can coexist within value chains, providiong that differentiation reflects strategic positioning rather than arbitrary prioritization. For BIPV manufacturers navigating ESPR compliance, particularly SMEs in early-stage ecodesign strategy development, the MCDA-AHP framework offers a practical, accessible tool offering pragmatic action addressing the prioritization of LLM-.driven actions and support circular economy success which does not require uniform industry transformation, but a coordinated differentiation where each actor's strategy coherently integrates environmental responsibility with business viability.

**Author Contributions:** Conceptualization, A.P.; methodology, A.P.; validation, A.P. and M.G.; formal analysis, A.P. and M.G.; investigation, A.P. and M.G.; resources, A.P. and M.G.; writing—original draft preparation, A.P.; writing—review and editing, A.P. and M.G; supervision, A.P.; project administration, A.P.; funding acquisition, A.P.. All authors have read and agreed to the published version of the manuscript.

**Funding:** this work has been carried out with support from the Horizon Europe project MC2.0 (www.mc2dot0.eu) with Grant Agreement nr. 101096139. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

**Institutional Review Board Statement:** not applicable.

**Informed Consent Statement:** not applicable.

**Data Availability Statement:** not applicable.

**Acknowledgments:** the authors gratefully acknowledge Glass to Power S.p.A. and Gualini S.p.A. for their voluntary participation as industrial case study partners, providing access to technical data and executive

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decision-makers for framework validation workshops. During the preparation of this study, the authors used Claude 4.5 Sonnet (Anthropic) for the purposes of: (1) synthesizing peer-reviewed literature on BIPV circularity and ESPR regulatory requirements to generate initial candidate ecodesign action pools (Stage 1, Methodology Section 2). The authors have reviewed and edited all LLM-generated outputs and take full responsibility for the accuracy, interpretation, and conclusions presented in this publication.

**Conflicts of Interest:** the authors declare no conflicts of interest. This research was conducted independently as part of the Horizon Europe project MC2.0 (Grant Agreement 101096139). The funders had no role in the study design, data collection, analysis, interpretation, manuscript preparation, or decision to publish. The case study companies (Glass to Power, GUALINI) participated voluntarily as industrial validation partners but did not influence the methodological framework development, priority classifications, or research conclusions. All findings, interpretations, and recommendations represent the authors' independent scientific judgment.

## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| AHP | Analytic Hierarchy Process |
| ASI | Aluminium Stewardship Initiative |
| BIM | Building Information Modeling |
| BIPV | Building-Integrated Photovoltaics |
| CE | Conformité Européenne (CE marking) |
| CEO | Chief Executive Officer |
| CPR | Construction Products Regulation (EU 305/2011) |
| CR | Consistency Ratio |
| DfD | Design for Disassembly |
| DfX | Design for X (generic design methodology) |
| DPP | Digital Product Passport |
| EN | European Norm (European Standard) |
| EPD | Environmental Product Declaration |
| EPDM | Ethylene Propylene Diene Monomer (rubber gasket material) |
| EPR | Extended Producer Responsibility |
| ESG | Environmental, Social and Governance |
| ESPR | Ecodesign for Sustainable Products Regulation (EU 2024/1781) |
| EU | European Union |
| F-D-A | Feasibility-Desirability-Affordability |
| G2P | Glass to Power (BIPV-IGU manufacturer case study company) |
| GHG | Greenhouse Gas |
| GUA | GUALINI (façade manufacturer case study company) |
| IGU | Insulated Glazing Unit |
| IoT | Internet of Things |
| IP | Ingress Protection (rating for electrical enclosures) |
| ISO | International Organization for Standardization |
| LCA | Life Cycle Assessment |
| LCC | Life Cycle Costing |
| LLM | Large Language Model |
| MCDA | Multi-Criteria Decision Analysis |
| MoSCoW | Must have, Should have, Could have, Won't have (prioritization method) |
| nZEB | Nearly Zero-Energy Building |
| O&M | Operations and Maintenance |
| P1, P2, P3, P4 | Priority levels (Must-Have, Should-Have, Could-Have, Won't-Have) |
| PCF | Product Carbon Footprint |
| PEB | Postiive-Energy Building |
| PV | Photovoltaic |
| PV-IGU | Photovoltaic Insulated Glazing Unit |
| SME | Small and Medium-sized Enterprise |
| SVHC | Substances of Very High Concern |
| TOPSIS | Technique for Order of Preference by Similarity to Ideal Solution |

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| | |
|---|---|
| TPE | Thermoplastic Elastomer |
| VOC | Volatile Organic Compound |
| WEEE | Waste Electrical and Electronic Equipment (EU Directive 2012/19) |
| ZEB | Zero-Energy Building |

## Appendix A

This appendix presents the complete ecodesign action portfolios developed and prioritized for the two industrial case study companies. The matrices provide detailed Feasibility-Desirability-Affordability (F-D-A) scoring, weighted priority scores (S), MoSCoW priority classifications (P1-P4), and authoritative references for all identified interventions aligned with ESPR 2024/1781 Annex V requirements.

Table A1 presents the 42 ecodesign actions for Glass to Power (G2P), a BIPV-IGU component manufacturer, comprising 30 common ESPR General actions (C1-C30) applicable across BIPV manufacturers and 12 system-specific actions (G2P1-G2P12) addressing component-level circularity challenges such as aluminum frame design, glass recycling partnerships, PV cell integration, and IGU cavity management.

Table A2 presents the 40 ecodesign actions for GUALINI, a BIPV façade system integrator, comprising the same 30 common ESPR General actions (C1-C30) with re-scored F-D-A values reflecting system-level complexity, and 10 system-specific actions (GUA1-GUA10) addressing façade assembly logistics, electrical integration, service business models, and supply chain coordination requirements.

**Table A1.** Glass to Power ecodesign matrix prioritization actions.

| ID | Goals (ESPR 2024 - Annex V) | Lifecycle Stage | Common/System-specific | Objectives and Product-Specific Design Actions | F | D | A | S | P | Notes and References |
|---|---|---|---|---|---|---|---|---|---|---|
| **C1** | Carbon footprint | All Lifecycle stages | ESPR General | Develop verified Carbon footprint (PCF) for DPP | 4 | 5 | 4 | 4.66 | P1 | [43–45] |
| **C2** | Carbon footprint | Manufacturing | ESPR General | Source low-carbon/local aluminium (<4 kg $CO_2e$/kg) from suppliers | 5 | 5 | 3 | 4.63 | P1 | [43,46,47] |
| **C3** | Carbon footprint | Manufacturing | ESPR General | Optimize transport mode selection (rail/truck) based on distance | 2 | 3 | 2 | 2.66 | P4 | [43,48,49] |
| **C4** | Carbon footprint | Manufacturing | ESPR General | Source from suppliers with renewable energy credentials | 3 | 4 | 3 | 3.66 | P2 | [50–52] |
| **G2P1** | Carbon footprint | Manufacturing | System-Specific (G2P Assembly) | Transition to 100% renewable energy for assembly facility | 5 | 4 | 5 | 4.34 | P1 | [51–53] |
| **C5** | Durability | Design | ESPR General | Declare and extend warranty period (target 10-15 years) | 4 | 5 | 3 | 4.47 | P1 | [54–56] |
| **G2P2** | Durability | Design | System-Specific (IGU) | Optimize thermal break design in IGU spacer system | 5 | 4 | 2 | 3.78 | P2 | [57,58] |

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| **G2P3** | Durability | Design | System-Specific (IGU) | Enhanced climate protection (tempered/laminated glass) | 5 | 4 | 4 | 4.16 | P1 | [59–61] |
| **C6** | Energy | Manufacturing | ESPR General | Source low-embodied energy materials from supply chain | 3 | 5 | 3 | 4.31 | P1 | [46,62,63] |
| **G2P4** | Energy | Use | System-Specific (PV) | Optimize PV cell arrangement for electrical efficiency | 4 | 4 | 4 | 4.00 | P1 | [56,64] |
| **C7** | Maintenance | Design | ESPR General | Design for inspectability at critical points | 4 | 5 | 4 | 4.66 | P1 | [65,66] |
| **C8** | Maintenance | Use | ESPR General | Integrate IoT remote monitoring system | 4 | 3 | 3 | 3.16 | P3 | [67–69] |
| **G2P5** | Maintenance | Use | System-Specific (PV) | Establish preventive maintenance protocols for PV-IGU | 5 | 4 | 4 | 4.16 | P1 | [69–71] |
| **C9** | Recoverability | End of Life | ESPR General | Document disassembly sequence in DPP | 4 | 3 | 4 | 3.34 | P3 | [1,72,73] |
| **C10** | Recoverability | End of Life | ESPR General | Partner with glass recyclers for closed-loop recovery | 3 | 3 | 2 | 2.81 | P4 | [74–76] |
| **C11** | Recoverability | End of Life | ESPR General | Establish WEEE-compliant take-back program | 2 | 4 | 2 | 3.31 | P3 | [77–79] |
| **C12** | Recyclability | Design | ESPR General | Create material passport for DPP (materials inventory) | 4 | 3 | 4 | 3.34 | P3 | [80–82] |
| **C13** | Recyclability | Design | ESPR General | Design dry fastening connections, eliminate permanent adhesives | 3 | 3 | 3 | 3.00 | P3 | [73,83,84] |
| **G2P6** | Recyclability | Design | System-Specific (IGU) | Replace butyl sealant with mechanical/velcro-type connections for IGU assembly | 2 | 2 | 2 | 2.00 | P4 | [85,86] |
| **G2P7** | Recyclability | Design | System-Specific (IGU) | Switch to low-VOC/certified structural silicone (avoiding non-recyclable sealants) | 4 | 3 | 3 | 3.16 | P3 | [87,88] |
| **C14** | Recycled | Manufacturing | ESPR General | Source high recycled aluminium (≥75%) from suppliers | 4 | 4 | 3 | 3.81 | P2 | [89–91] |
| **G2P8** | Recycled | Manufacturing | System-Specific (IGU) | Source glass with 40-60% recycled cullet from suppliers | 3 | 3 | 3 | 3.00 | P3 | [92–94] |
| **G2P9** | Recycled | Manufacturing | System-Specific (IGU) | Source spacer bars with recycled content from suppliers | 3 | 2 | 2 | 2.16 | P4 | [43,95,96] |
| **C15** | Reliability | Manufacturing | ESPR General | Obtain EPD certification (EN 15804+A2) for product | 5 | 5 | 3 | 4.63 | P1 | [1,41,43] |

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| **C16** | Reliability | Manufacturing | ESPR General | Implement quality control labeling (CE marking per CPR) | 5 | 5 | 4 | 4.81 | P1 | [97–99] |
| **G2P10** | Remanufacturability | End of Life | System-Specific (IGU) | Design for IGU cavity refilling/upgrading (argon top-up, film insertion) | 3 | 3 | 3 | 3.00 | P3 | [86,100,101] |
| **C17** | Repairability | Manufacturing & Use | ESPR General | Implement DPP system per ESPR Art. 9-13 | 4 | 5 | 3 | 4.47 | P1 | [1,102,103] |
| **C18** | Repairability | Use | ESPR General | Publish repair/maintenance documentation via DPP | 5 | 4 | 5 | 4.34 | P1 | [1,69] |
| **C19** | Repairability | Design | ESPR General | Design accessible junction boxes/electrical connections | 4 | 4 | 5 | 4.19 | P1 | [104–106] |
| **C20** | Repairability | Design | ESPR General | Provide 3D models/digital twins for replaceable components | 3 | 2 | 4 | 2.53 | P4 | [107–109] |
| **C21** | Resource | Design | ESPR General | Optimize component-to-frame ratio for material efficiency | 4 | 3 | 4 | 3.34 | P3 | [65,110] |
| **C22** | Resource | Manufacturing | ESPR General | Implement nesting optimization, reduce scrap during cutting/machining | 4 | 3 | 4 | 3.34 | P3 | [111–113] |
| **C23** | Reusability | Design | ESPR General | Standardize components across product variants (modular design) | 5 | 3 | 4 | 3.50 | P2 | [114–116] |
| **G2P11** | Reusability | Design | System-Specific (IGU/PV) | Standardize PV frame components (junction boxes, cable glands, mounting pins) | 5 | 3 | 4 | 3.50 | P2 | [117,118] |
| **C24** | Substances | Manufacturing | ESPR General | Source materials with VOC-free/low-VOC certifications from suppliers | 5 | 4 | 4 | 4.16 | P1 | [87,119,120] |
| **C25** | Substances | Manufacturing | ESPR General | Document SVHC substances in DPP per ESPR Art. 7(5) | 4 | 3 | 4 | 3.34 | P3 | [121–123] |
| **C26** | Upgradability | Design | ESPR General | Design modular electrical connections for future component upgrades | 3 | 4 | 3 | 3.66 | P2 | [60] |
| **C27** | Waste | Manufacturing | ESPR General | Implement scrap recovery systems (Al to remelting, glass cullet return) | 4 | 3 | 4 | 3.34 | P3 | [4,91,112] |
| **C28** | Waste | Manufacturing | ESPR General | Zero-waste-to-landfill target for manufacturing operations | 3 | 3 | 3 | 3.00 | P3 | [112,124,125] |

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| **C29** | Waste | End of Life | ESPR General | Design for selective demolition and component separation | 3 | 3 | 3 | 3.00 | P3 | [73,126,127] |
| **C30** | Water | Manufacturing | ESPR General | Source ASI-certified aluminium (water stewardship criteria) | 5 | 3 | 4 | 3.50 | P2 | [90,128,129] |

**Table A2.** Gualini ecodesign matrix prioritization actions.

| ID | Goals (ESPR 2024 - Annex V) | Lifecycle Stage | Common/System-specific | Objectives and Product-Specific Design Actions | FDA | S | P | Notes and References |
|---|---|---|---|---|---|---|---|---|
| **C1** | Carbon footprint | All Lifecycle stages | ESPR General | Develop verified Carbon footprint (PCF) for DPP | 4 5 4 | 4,26 | P1 | [43–45] |
| **C2** | Carbon footprint | Manufacturing | ESPR General | Source low-carbon/local aluminium (<4 kg $CO_2$e/kg) from suppliers | 5 5 3 | 3,73 | P2 | [43,46,47] |
| **C3** | Carbon footprint | Manufacturing | ESPR General | Optimize transport mode selection (rail/truck) based on distance | 4 4 5 | 4,63 | P1 | [43,48,49] |
| **C4** | Carbon footprint | Manufacturing | ESPR General | Source from suppliers with renewable energy credentials | 3 4 3 | 3,26 | P3 | [50–52] |
| **GUA1** | Carbon footprint | Manufacturing | System-Specific (Façade Assembly) | Transition to 100% renewable energy for assembly/off-site manufacturing facility | 5 4 5 | 4,74 | P1 | [51–53] |
| **C5** | Durability | Design | ESPR General | Declare and extend warranty period (target 10-15 years) | 4 5 3 | 3,63 | P2 | [54–56] |
| **GUA2** | Durability | Design | System-Specific (Façade) | Design polymer thermal break profiles for disassembly in façade frames | 3 3 3 | 3,00 | P3 | [130,131] |
| **C6** | Energy | Manufacturing | ESPR General | Source low-embodied energy materials from supply chain | 4 4 3 | 3,37 | P3 | [46,62,63] |

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|---|---|---|---|---|---|---|---|---|---|---|
| **C7** | Maintenance | Design | ESPR General | Design for inspectability at critical points | 4 | 5 | 4 | 4,26 | P1 | [65,66] |
| **C8** | Maintenance | Use | ESPR General | Integrate IoT remote monitoring system | 4 | 3 | 3 | 3,11 | P3 | [67–69] |
| **GUA3** | Maintenance | Use | System-Specific (Façade) | Establish preventive maintenance service contracts with remote diagnostics for façade-integrated BIPV | 5 | 3 | 3 | 3,21 | P3 | [132–134] |
| **C9** | Recoverability | End of Life | ESPR General | Document disassembly sequence in DPP | 4 | 3 | 4 | 3,74 | P2 | [1,72,73] |
| **GUA4** | Recoverability | End of Life | System-Specific (Façade Supply Chain) | Coordinate with PV-IGU supplier (G2P) for closed-loop glass recovery | 3 | 4 | 3 | 3,26 | P3 | [92–94] |
| **C10** | Recoverability | End of Life | ESPR General | Partner with glass recyclers for closed-loop recovery | 3 | 3 | 2 | 2,37 | P4 | [74–76] |
| **C11** | Recoverability | End of Life | ESPR General | Establish WEEE-compliant take-back program | 2 | 4 | 2 | 2,52 | P4 | [77–79] |
| **GUA5** | Recoverability | End of Life | System-Specific (Façade) | Partner with aluminium remelting facilities for closed-loop façade frame recovery | 5 | 3 | 4 | 3,85 | P2 | [135–137] |
| **C12** | Recyclability | Design | ESPR General | Create material passport for DPP (materials inventory) | 4 | 3 | 4 | 3,74 | P2 | [80–82] |
| **C13** | Recyclability | Design | ESPR General | Design dry fastening connections, eliminate permanent adhesives | 3 | 3 | 3 | 3,00 | P3 | [73,83,84] |

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|---|---|---|---|---|---|---|---|---|---|---|
| **GUA6** | Recyclability | Design | System-Specific (Façade) | Replace EPDM gaskets with thermoplastic elastomer (TPE) for façade sealing | 2 | 2 | 3 | 2,63 | P4 | [138,139] |
| **GUA7** | Recyclability | Design | System-Specific (Façade) | Design junction boxes with tool-free access (quarter-turn latches, not glued seals) | 5 | 3 | 4 | 3,85 | P2 | [140–142] |
| **C14** | Recycled | Manufacturing | ESPR General | Source high recycled aluminium (≥75%) from suppliers | 4 | 4 | 3 | 3,37 | P3 | [89–91] |
| **C15** | Reliability | Manufacturing | ESPR General | Obtain EPD certification (EN 15804+A2) for product | 4 | 5 | 3 | 3,63 | P2 | [1,41,43] |
| **C16** | Reliability | Manufacturing | ESPR General | Implement quality control labeling (CE marking per CPR) | 5 | 5 | 4 | 4,37 | P1 | [97–99,143] |
| **GUA8** | Reliability | Manufacturing | System-Specific (Façade) | Develop supply chain qualification protocol for electrical component suppliers (EPD, SVHC, Repairability data) | 3 | 4 | 3 | 3,26 | P3 | [63,128] |
| **C17** | Repairability | Manufacturing & Use | ESPR General | Implement DPP system per ESPR Art. 9-13 | 3 | 5 | 3 | 3,52 | P2 | [1,102,103] |
| **C18** | Repairability | Use | ESPR General | Publish repair/maintenance documentation via DPP | 5 | 4 | 5 | 4,74 | P1 | [1,69] |
| **C19** | Repairability | Design | ESPR General | Design accessible junction boxes/electrical connections | 4 | 4 | 5 | 4,63 | P1 | [104–106] |
| **GUA9** | Repairability | Design | System-Specific (Façade) | Use corrugated conduit with snap- | 5 | 4 | 5 | 4,74 | P1 | [144–146] |

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| | | | | fit cable routing (no permanent installation) | | | | | | |
| **GUA10** | Repairability | Design | System-Specific (Façade) | Specify IEC 67/IP68 cable glands (not permanent sealants) for all electrical penetrations | 5 | 5 | 4 | 4,37 | P1 | [147–149] |
| **C20** | Repairability | Design | ESPR General | Provide 3D models/digital twins for replaceable components | 3 | 2 | 4 | 3,37 | P3 | [107–109] |
| **C21** | Resource | Design | ESPR General | Optimize component-to-frame ratio for material efficiency | 4 | 3 | 4 | 3,74 | P2 | [65,110] |
| **C22** | Resource | Manufacturing | ESPR General | Implement nesting optimization, reduce scrap during cutting/machining | 5 | 4 | 4 | 4,11 | P1 | [111–113] |
| **C23** | Reusability | Design | ESPR General | Standardize components across product variants (modular design) | 5 | 4 | 4 | 4,11 | P1 | [114–116] |
| **C24** | Substances | Manufacturing | ESPR General | Source materials with VOC-free/low-VOC certifications from suppliers | 5 | 5 | 4 | 4,37 | P1 | [87,119,120] |
| **C25** | Substances | Manufacturing | ESPR General | Document SVHC substances in DPP per ESPR Art. 7(5) | 4 | 4 | 4 | 4,00 | P1 | [121–123] |
| **C26** | Upgradability | Design | ESPR General | Design modular electrical connections for future component upgrades | 3 | 4 | 3 | 3,26 | P3 | [60] |
| **C27** | Waste | Manufacturing | ESPR General | Implement scrap recovery systems (Al to remelting, glass cullet return) | 4 | 3 | 4 | 3,74 | P2 | [4,91,112] |

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| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **C28** | Waste | Manufacturing | ESPR General | Zero-waste-to-landfill target for manufacturing operations | 3 | 3 | 3 | 3,00 | P3 | [112,124,125] |
| **C29** | Waste | End of Life | ESPR General | Design for selective demolition and component separation | 3 | 3 | 3 | 3,00 | P3 | [73,126,127] |
| **C30** | Water | Manufacturing | ESPR General | Source ASI-certified aluminium (water stewardship criteria) | 5 | 3 | 4 | 3,85 | P2 | [90,128,129] |

## References


1. European Parliament Regulation - EU - 2024/1781 - EN - EUR-Lex Available online: https://eur-lex.europa.eu/eli/reg/2024/1781/oj/eng (accessed on 18 April 2025).
2. International Definitions of "BIPV"; IEA PVPS, 2018;
3. European Parliament Directive - EU - 2012/19 - EN - EUR-Lex;
4. elisa.andreotti International Aluminium Institute Publishes Global Recycling Data. *International Aluminium Institute* 2020.
5. Eco-Indicator 99 | Manuals. *PRé Sustainability* 2014.
6. ReCiPe. PRé Sustainability 2016.
7. Circularity Assessment Framework Available online: https://www.oneplanetnetwork.org/programmes/circular-built-environment/National-Circularity-Assessment-Framework (accessed on 26 November 2025).
8. Material Circularity Indicator | Ellen MacArthur Foundation Available online: https://www.ellenmacarthurfoundation.org/material-circularity-indicator (accessed on 26 November 2025).
9. Circular Transition Indicators (CTI) | WBCSD Available online: https://www.wbcsd.org/actions/circular-transition-indicators/ (accessed on 26 November 2025).
10. Design Methodologies for Conventional and Additive Manufacturing. In *Digital Manufacturing*; Elsevier, 2022; pp. 97–143.
11. The State of AI: Global Survey 2025 | McKinsey Available online: https://www.mckinsey.com/capabilities/quantumblack/our-insights/the-state-of-ai (accessed on 9 January 2026).
12. Brynjolfsson, E.; Li, D.; Raymond, L.R. NBER WORKING PAPER SERIES.
13. Ji, Z.; Lee, N.; Frieske, R.; Yu, T.; Su, D.; Xu, Y.; Ishii, E.; Bang, Y.J.; Madotto, A.; Fung, P. Survey of Hallucination in Natural Language Generation. *ACM Comput. Surv.* **2023**, *55*, 248:1-248:38, doi:10.1145/3571730.
14. Shneiderman, B. Human-Centered Artificial Intelligence: Reliable, Safe & Trustworthy. *International Journal of Human–Computer Interaction* **2020**, *36*, 495–504, doi:10.1080/10447318.2020.1741118.
15. Optimization of the Weighted Linear Combination Method for Agricultural Land Suitability Evaluation Considering Current Land Use and Regional Differences Available online: https://www.mdpi.com/2071-1050/12/23/10134 (accessed on 26 November 2025).
16. Baloyi, V.D.; Meyer, L.D. The Development of a Mining Method Selection Model through a Detailed Assessment of Multi-Criteria Decision Methods. *Results in Engineering* **2020**, *8*, 100172, doi:10.1016/j.rineng.2020.100172.


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Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 February 2026 doi:10.20944/preprints202602.1710.v1




17. Malczewski, J. On the Use of Weighted Linear Combination Method in GIS: Common and Best Practice Approaches. *Transactions in GIS* **2000**, *4*, 5–22, doi:10.1111/1467-9671.00035.
18. Behzadian, M.; Khanmohammadi Otaghsara, S.; Yazdani, M.; Ignatius, J. A State-of the-Art Survey of TOPSIS Applications. *Expert Systems with Applications* **2012**, *39*, 13051–13069, doi:10.1016/j.eswa.2012.05.056.
19. Weighted Scoring Model: Step-by-Step Implementation Guide Available online: https://productschool.com/blog/product-fundamentals/weighted-scoring-model (accessed on 21 November 2025).
20. Nearly-Zero Energy and Zero-Emission Buildings - European Commission Available online: https://energy.ec.europa.eu/topics/energy-efficiency/energy-performance-buildings/nearly-zero-energy-and-zero-emission-buildings_en (accessed on 26 November 2025).
21. Likert, R. A Technique for the Measurement of Attitudes. *Archives of Psychology* **1932**, *22 140*, 55–55.
22. Saaty, R.W. The Analytic Hierarchy Process—What It Is and How It Is Used. *Mathematical Modelling* **1987**, *9*, 161–176, doi:10.1016/0270-0255(87)90473-8.
23. Saaty, T.L. The Hierarchy Analytic Process 1980.
24. ISO 14040:2006 - Environmental Management — Life Cycle Assessment — Principles and Framework Available online: https://www.iso.org/standard/37456.html (accessed on 26 November 2025).
25. Home \ Anthropic Available online: https://www.anthropic.com/ (accessed on 9 January 2026).
26. Case Method Fast-Track: A Rad Approach - Clegg, Dai; Barker, Richard: 9780201624328 - AbeBooks Available online: https://www.abebooks.it/9780201624328/Case-Method-Fast-Track-Rad-Approach-020162432X/plp (accessed on 26 November 2025).
27. Eisenhower Matrix. *ProductPlan*.
28. Business, A. MoSCoW Prioritisation - DSDM Project Framework Handbook | Agile Business Consortium Available online: https://www.agilebusiness.org/dsdm-project-framework/moscow-prioririsation.html (accessed on 31 December 2025).
29. Glass to Power SpA – Vetrata Fotovoltaica Trasparente Isolante Available online: https://www.glasstopower.com/ (accessed on 31 January 2025).
30. Gualini | Facciate Continue e Finestre Available online: https://www.gualini.eu/en (accessed on 31 December 2025).
31. Heli-On: Insulating Photovoltaic Glazing – Glass to Power SpA.
32. Triantaphyllou, E.; Sánchez, A. A Sensitivity Analysis Approach for Some Deterministic Multi-Criteria Decision-Making Methods. *Decision Sciences* **1997**, *28*, 151–194, doi:10.1111/j.1540-5915.1997.tb01306.x.
33. Alan Agresti Statistical Methods for the Social Sciences, Global Edition; Pearson Education Limited, 2018;
34. DiMaggio, P.J.; Powell, W.W. The Iron Cage Revisited: Institutional Isomorphism and Collective Rationality in Organizational Fields. *American Sociological Review* **1983**, *48*, 147–160, doi:10.2307/2095101.
35. Hwang, C.-L.; Yoon, K. *Multiple Attribute Decision Making*; Lecture Notes in Economics and Mathematical Systems; Springer: Berlin, Heidelberg, 1981; Vol. 186; ISBN 978-3-540-10558-9.
36. Bocken, N.M.P.; de Pauw, I.; Bakker, C.; van der Grinten, B. Product Design and Business Model Strategies for a Circular Economy. *Journal of Industrial and Production Engineering* **2016**, *33*, 308–320, doi:10.1080/21681015.2016.1172124.
37. Porter, M.E.; van der Linde, C. Toward a New Conception of the Environment-Competitiveness Relationship. *Journal of Economic Perspectives* **1995**, *9*, 97–118, doi:10.1257/jep.9.4.97.
38. Gluch, P.; Baumann, H. The Life Cycle Costing (LCC) Approach: A Conceptual Discussion of Its Usefulness for Environmental Decision-Making. *Building and Environment* **2004**, *39*, 571–580, doi:10.1016/j.buildenv.2003.10.008.
39. ISO 15686-5:2017 Available online: https://www.iso.org/standard/61148.html (accessed on 12 January 2026).
40. Behzadian, M.; Khanmohammadi Otaghsara, S.; Yazdani, M.; Ignatius, J. A State-of the-Art Survey of TOPSIS Applications. *Expert Systems with Applications* **2012**, *39*, 13051–13069, doi:10.1016/j.eswa.2012.05.056.
41. LCA & EPDs for Construction & Manufacturing | One Click LCA Available online: https://oneclicklca.com/en-gb/ (accessed on 9 January 2026).
42. Tally Available online: https://choosetally.com/ (accessed on 9 January 2026).


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Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 February 2026
doi:10.20944/preprints202602.1710.v1




43. EN 15804:2012+A2:2019 - UNI Ente Italiano Di Normazione Available online: https://store.uni.com/en-15804-2012-a2-2019 (accessed on 13 January 2026).
44. ISO 14067:2018 - Greenhouse Gases — Carbon Footprint of Products Available online: https://www.iso.org/standard/71206.html (accessed on 13 January 2026).
45. Product Standard | GHG Protocol Available online: https://ghgprotocol.org/product-standard (accessed on 13 January 2026).
46. European Aluminium Available online: https://european-aluminium.eu/ (accessed on 13 January 2026).
47. Hydro REDUXA Available online: https://www.hydro.com/it/global/Alluminio/products/alluminio-a-basso-tenore-di-carbonio-e-riciclato/alluminio-a-bassa-impronta-di-carbonio/reduxa/ (accessed on 13 January 2026).
48. Corporate Value Chain (Scope 3) Standard | GHG Protocol Available online: https://ghgprotocol.org/corporate-value-chain-scope-3-standard (accessed on 13 January 2026).
49. EcoTransIT World. *EcoTransIT World* | 2021.
50. RE100 - Join Hundreds of Ambitious Companies Committed to Using 100% Renewable Electricity Available online: https://www.there100.org/ (accessed on 13 January 2026).
51. CDP Supply Chain Membership Available online: https://www.cdp.net/en/supply-chain (accessed on 13 January 2026).
52. ISO 50001:2018 Available online: https://www.iso.org/standard/69426.html (accessed on 13 January 2026).
53. RE100 - Join Hundreds of Ambitious Companies Committed to Using 100% Renewable Electricity Available online: https://www.there100.org/ (accessed on 16 February 2026).
54. EN 13947:2006 - UNI Ente Italiano Di Normazione Available online: https://http.uni.com/en-13947-2006 (accessed on 13 January 2026).
55. Prieto-Castrillo, F.; Núñez, N.; Vázquez, M. Warranty Assessment of Photovoltaic Modules Based on a Degradation Probabilistic Model. *Progress in Photovoltaics* **2020**, *28*, 1308–1321, doi:10.1002/pip.3328.
56. Reliability and Performance of Photovoltaic Systems. *IEA-PVPS*.
57. EN ISO 10077-2:2012 - UNI Ente Italiano Di Normazione Available online: https://store.uni.com/en-iso-10077-2-2012 (accessed on 16 February 2026).
58. Glass for Europe - Trade Association of European Flat Glass Value Chain Available online: https://glassforeurope.com/ (accessed on 16 February 2026).
59. EN ISO 12543-1:2021 - UNI Ente Italiano Di Normazione Available online: https://store.uni.com/en-iso-12543-1-2021 (accessed on 16 February 2026).
60. Martín Chivelet, N.; Kapsis, C.; Frontini, F. *Building-Integrated Photovoltaics: A Technical Guidebook*; 1st ed.; Routledge: New York, 2024; ISBN 978-1-003-43224-1.
61. EN 14449:2005 - UNI Ente Italiano Di Normazione Available online: https://store.uni.com/en-14449-2005 (accessed on 16 February 2026).
62. Embodied Carbon Footprint Database. *Circular Ecology*.
63. One Platform, Global Visibility. Your Sustainability Intelligence Software. Available online: https://ecovadis.com/ (accessed on 13 January 2026).
64. Shahid, J.; Mittag, M.; Heinrich, M. A MULTIDIMENSIONAL OPTIMIZATION APPROACH TO IMPROVE MODULE EFFICIENCY, POWER AND COSTS. **2018**.
65. Glass Structures & Engineering Available online: https://link.springer.com/journal/40940 (accessed on 17 February 2026).
66. Standard Guide for Conducting Inspections of Building Facades for Unsafe Conditions Available online: https://store.astm.org/e2841-19.html (accessed on 17 February 2026).
67. Ftirich, A.; Bouaziz, B.; Bacha, F. Real-Time Monitoring for a Building-Integrated Photovoltaic System Based on the Internet of Things and a Web Application. *Engineering, Technology & Applied Science Research* **2024**, *14*, 15931–15937, doi:10.48084/etasr.7531.
68. ISO 55000:2024 Available online: https://www.iso.org/standard/83053.html (accessed on 17 February 2026).
69. IEA PVPS Task 13 Guidelines for Operation and Maintenance of Photovoltaic Power Plants in Different Climates; 2022;


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Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 February 2026 doi:10.20944/preprints202602.1710.v1




70. Walker, H.A. Best Practices for Operation and Maintenance of Photovoltaic and Energy Storage Systems; 3rd Edition; 2018; p. NREL/TP-7A40-73822, 1489002;
71. IEC TS 62446-3:2017 Available online: https://webstore.iec.ch/en/publication/28628 (accessed on 16 February 2026).
72. Circular Buildings Toolkit Available online: https://ce-toolkit.dhub.arup.com/ (accessed on 17 February 2026).
73. ISO 20887:2020 Available online: https://www.iso.org/standard/69370.html (accessed on 17 February 2026).
74. levelup Treglas – The Circular Economy Is the Best Way to Reduce Emissions. *Treglas* 2024.
75. ricardo A Circular Economy Act to Support Flat Glass Closed-Loop Recycling Systems. *Glass for Europe* 2025.
76. Vlakglasrecycling Nederland - Home Available online: https://www.vlakglasrecycling.nl/index.php?page=home-en (accessed on 17 February 2026).
77. European Parliament Directive 2010/41/EU of the European Parliament and of the Council of 7 July 2010. In *Core EU Legislation*; Macmillan Education UK: London, 2015; pp. 352–355 ISBN 978-1-137-54501-5.
78. Governance. CdC RAEE | Centro di Coordinamento RAEE.
79. Risks, C.& EPR Take-Back Program Monitoring. *Compliance & Risks* 2025.
80. Materials Passports. *BAMB*.
81. Pracucci, A.; Giovanardi, M. Design of a Sensor-Based Digital Product Passport for Low-Tech Manufacturing: Traceability and Environmental Monitoring in Bio-Block Production. *Sensors* **2025**, *25*, 5653, doi:10.3390/s25185653.
82. End-of-Life Management Solar Photovoltaic Panels Available online: https://www.irena.org/publications/2016/Jun/End-of-life-management-Solar-Photovoltaic-Panels (accessed on 17 February 2026).
83. C2C Certified® Circularity - Cradle to Cradle Products Innovation Institute Available online: https://c2ccertified.org/the-standard/circularity-certification (accessed on 17 February 2026).
84. Hartwell, R.; Macmillan, S.; Overend, M. Circular Economy of Façades: Real-World Challenges and Opportunities. *Resources, Conservation and Recycling* **2021**, *175*, 105827, doi:10.1016/j.resconrec.2021.105827.
85. Automated Insulated Glass Separation with IG2Pieces Available online: https://www.hegla.com/en/products/isolierglas-trennen-ig2pieces/ (accessed on 16 February 2026).
86. Teich, M.; Scherer, C.; Schuster, M.; Brandenstein, M.; Elstner, M. Reuse and Remanufacturing of Insulated Glass Units. *Glass Struct Eng* **2024**, *9*, 339–356, doi:10.1007/s40940-024-00276-x.
87. GEV Emicode Available online: https://www.emicode.com/en/home/ (accessed on 16 February 2026).
88. Low VOC Products for High Performing Buildings Available online: https://www.dow.com/en-us/market/mkt-building-construction/sustainability/building-construction/low-voc-products.html (accessed on 16 February 2026).
89. Hydro CIRCAL Recycled Aluminium Available online: https://www.hydro.com/en/global/aluminium/products/low-carbon-and-recycled-aluminium/recycled-aluminium/hydro-circal/ (accessed on 14 October 2024).
90. ASI Performance Standard. Aluminium Stewardship Initiative.
91. Recycling - European Aluminium Available online: https://european-aluminium.eu/projets/recycling/ (accessed on 17 February 2026).
92. Recycling Europe; FEAD; Ferver From Flat to Circular: Rethinking Glass in Construction; 2025;
93. Glass for Europe Recycling of End-of-Life Building Glass A Powerful Tool to Reduce CO2 Emissions; 2024;
94. Towards a Quality Protocol for Enabling the Reuse of Post-Consumer Flat Glass | Glass Structures & Engineering | Springer Nature Link Available online: https://link.springer.com/article/10.1007/s40940-023-00233-0 (accessed on 16 February 2026).
95. Elegance Meets Responsibility: Warm Edge in All Black with Recycled Content Available online: https://it.glassglobal.com/news/elegance-meets-responsibility-warm-edge-in-all-black-with-recycled-content-34359.html (accessed on 17 February 2026).
96. Swisspacer_Ultimate-Nyxé Available online: https://www.swisspacer.com/en/products/ultimate/ultimate-nyxe (accessed on 17 February 2026).


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Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 February 2026 | doi:10.20944/preprints202602.1710.v1




97. EN 1279-5:2018 - Glass in Building - Insulating Glass Units - Part 5: Available online: https://standards.iteh.ai/catalog/standards/cen/4440f830-5f8a-4514-840a-c2e03a758dfa/en-1279-5-2018?srsltid=AfmBOopsY8xgpdqpPQgVDUszV1SHrz-vJEM15OWCCCDoKhhcp8_c_1jd (accessed on 17 February 2026).
98. Construction Products Regulation Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52016DC0445 (accessed on 19 March 2025).
99. CE Marking - Internal Market, Industry, Entrepreneurship and SMEs Available online: https://single-market-economy.ec.europa.eu/single-market/goods/ce-marking_en (accessed on 17 February 2026).
100. Harrington, E.; Carmichael, C. Project Case Study: Empire State Building.
101. Reuse and Remanufacturing of Insulated Glass Units | Glassonweb.Com Available online: http://www.glassonweb.com/article/reuse-and-remanufacturing-insulated-glass-units (accessed on 17 February 2026).
102. European Parliament *Regulation (EU) 2024/3110*; **2024**.
103. CIRPASS – Digital Product Passport Available online: https://cirpassproject.eu/ (accessed on 17 February 2026).
104. Volberg, G. Junction Boxes for Photovoltaic Modules – Qualification and Tests.
105. Photovoltaic Junction Box Available online: https://www.telegaertner.com/en/product-highlights/photovoltaic-junction-box (accessed on 17 February 2026).
106. ARUP Guideline for Building Services Design; 2019;
107. Wang, W.; Xu, K.; Song, S.; Bao, Y.; Xiang, C. From BIM to Digital Twin in BIPV: A Review of Current Knowledge. *Sustainable Energy Technologies and Assessments* **2024**, *67*, 103855, doi:10.1016/j.seta.2024.103855.
108. Thomsen, M.R.; Nicholas, P.; Chiujdea, R.-S.; Nielsen, S.D.; Sonne, K.; Eppinger, C. Additive Manufacturing for Repair: Continual Construction Through Bio-Based Materials. *3D Printing and Additive Manufacturing* **2025**, *12*, 112–121, doi:10.1089/3dp.2023.0344.
109. 3D Printing Cable Fasteners and Clicks – Raise3D: Reliable, Industrial Grade 3D Printer Available online: https://www.raise3d.com/blog/3d-printing-cable-fasteners-and-clicks/ (accessed on 17 February 2026).
110. Bakmohammadi, P.; Narjabadifam, N.; Jamshidi, M.; Gül, M. A Holistic Framework to Optimize Embedding PV Systems into Building Façades. *Applied Energy* **2025**, *382*, 125288, doi:10.1016/j.apenergy.2025.125288.
111. Abdou, K.; Schaaf, N.; Struckmeier, F.; Braun, J.; Bhat Keelanje Srinivas, P.; Ottnad, J.; Huber, M.F. Nestability: A Deep Learning Oracle for Nesting Scrap Prediction in Manufacturing Industry. *Resources, Conservation and Recycling* **2024**, *205*, 107540, doi:10.1016/j.resconrec.2024.107540.
112. ISO 14001:2015 Available online: https://www.iso.org/standard/60857.html (accessed on 17 February 2026).
113. Rausch, C.; Sanchez, B.; Haas, C. Topology Optimization of Architectural Panels to Minimize Waste during Fabrication: Algorithms for Panel Unfolding and Nesting. *Journal of Construction Engineering and Management* **2021**, *147*, 05021006, doi:10.1061/(ASCE)CO.1943-7862.0002089.
114. EOTA Modular Construction Standard EAD 130087-00-0204; **2017**.
115. ISO 21723:2019 Available online: https://www.iso.org/standard/71507.html (accessed on 17 February 2026).
116. Azadi, S.; Nourian, P. GoDesign - A Modular Generative Design Framework for Mass-Customization and Optimization in Architectural Design.; Novi Sad, Serbia, 2021; pp. 285–294.
117. IEA-PVPS; IEA-PVPS Task 15 Advancing BIPV Standardization: Addressing Regulatory Gaps and Performance Challenges; 2024;
118. Chowdhury, P.; Chowdhury, H.; Chowdhury, T.; Corkish, R. Standardization as a Pathway to a Circular PV Industry: Addressing Material Recovery and Design Challenges. *Solar Energy Materials and Solar Cells* **2026**, *296*, 114067, doi:10.1016/j.solmat.2025.114067.
119. REACH VOC Available online: https://echa.europa.eu/it/substances-restricted-under-reach (accessed on 17 February 2026).
120. RoHS Directive - Environment - European Commission Available online: https://environment.ec.europa.eu/topics/waste-and-recycling/rohs-directive_en (accessed on 17 February 2026).


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Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 February 2026 doi:10.20944/preprints202602.1710.v1




121. REACH SVHC Available online: https://echa.europa.eu/it/candidate-list-table (accessed on 17 February 2026).
122. SCIP - ECHA Available online: https://echa.europa.eu/it/scip (accessed on 17 February 2026).
123. European Parliament *Regulation (EC) 1907/2006*; **2006**.
124. Zero Waste Europe Available online: https://zerowasteeurope.eu/ (accessed on 17 February 2026).
125. Home | GBCI True Available online: https://true.gbci.org/ (accessed on 17 February 2026).
126. W115 - Achieving Circularity in the Built Environment. *CIB*.
127. European Commission. Directorate General for Internal Market, Industry, Entrepreneurship and SMEs. EU Construction & Demolition Waste Management Protocol Including Guidelines for Pre-Demolition and Pre-Renovation Audits of Construction Works: Updated Edition 2024.; Publications Office: LU, 2024;
128. ISO 20400:2017 Available online: https://www.iso.org/standard/63026.html (accessed on 17 February 2026).
129. Home | Alliance for Water Stewardship 2023.
130. Kim, M. Efficiency and Feasibility of the Disassembly Process for Curtain Wall Systems.
131. Piccioni, V.; Leschok, M.; Lydon, G.; Cheibas, I.; Hischier, I.; Dillenburger, B.; Kohler, M.; Gramazio, F.; Schlueter, A. Printing Thermal Performance: An Experimental Exploration of 3DP Polymers for Facade Applications. *IOP Conf. Ser.: Earth Environ. Sci.* **2023**, *1196*, 012063, doi:10.1088/1755-1315/1196/1/012063.
132. Hamza, A.; Ali, Z.; Dudley, S.; Saleem, K.; Uneeb, M.; Christofides, N. A Multi-Stage Review Framework for AI-Driven Predictive Maintenance and Fault Diagnosis in Photovoltaic Systems. *Applied Energy* **2025**, *393*, 126108, doi:10.1016/j.apenergy.2025.126108.
133. Azcárate-Aguerre, J.F.; den Heijer, A.C.; Arkesteijn, M.H.; Vergara d'Alençon, L.M.; Klein, T. Facades-as-a-Service: Systemic Managerial, Financial, and Governance Innovation to Enable a Circular Economy for Buildings. Lessons Learnt from a Full-Scale Pilot Project in the Netherlands. *Front. Built Environ.* **2023**, *9*, doi:10.3389/fbuil.2023.1084078.
134. ARUP; Ellen MacArthur Foundation From Principles to Practices Realising the Value of Circular Economy in Real Estate; 2020;
135. Recycling Services: Future-Proof & Sustainable Available online: https://www.speira.com/markets-products/recycling-services/ (accessed on 17 February 2026).
136. Recycled Aluminium - The Endless Loop - TECHNAL Available online: https://www.technal.com/en-int/professionals/explore/materials (accessed on 17 February 2026).
137. Centroal - Chi siamo | CENTROAL Available online: https://www.centroal.it/capitolo.php?idSEZ=1 (accessed on 17 February 2026).
138. Kraiburg TPE Outlines Circular Economy Pathways for Thermoplastic Elastomers | European Rubber Journal Available online: https://www.european-rubber-journal.com/article/2098569/kraiburg-tpe-outlines-circular-economy-pathways-for-thermoplastic-elastomers (accessed on 17 February 2026).
139. admin EPDM vs TPE Differences. *V.A.V. Group* 2025.
140. Snap Fit Joints Design Guideline Available online: https://www.eycpu.com/blog/snap-fit-joints-design-guideline/ (accessed on 17 February 2026).
141. QuickMount® Components. *IronRidge*.
142. Quick Release Fasteners - Quarter Turn & Ball Lock Fasteners | Imao Available online: https://www.imao.com/en/products/onetouchchakudatsu-en.html (accessed on 17 February 2026).
143. UNI EN 13830:2020 Available online: http://store.uni.com/catalogo/uni-en-13830-2020 (accessed on 29 April 2021).
144. EVS-EN 61386-1:2008/A1:2019 Available online: https://www.evs.ee/en/evs-en-61386-1-2008-a1-2019 (accessed on 17 February 2026).
145. Legrande RTA CONDUIT SYST EMS 2013.
146. Cable Clips & Cleats | Essentra Components Available online: https://www.essentracomponents.mx/en-us/fiber-wire-cable-management/cable-clips-cleats/ (accessed on 17 February 2026).
147. CEI - CEI EN 60529 Available online: https://mycatalogo.ceinorme.it/cei/item/000003227?sso=y (accessed on 17 February 2026).
148. EN 15520; **2004**.


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Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 February 2026 doi:10.20944/preprints202602.1710.v1



149. HELUKABEL | Cable Glands Available online: https://shop.helukabel.com/dk-en/cable-glands (accessed on 17 February 2026).

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