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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 Artificial Intelligence (AI) framework enabling rapid ecodesign prioritization for Ecodesign for Sustainable Products Regulation (ESPR) compliance while demonstrating Large Language Model (LLM) integration in sustainability strategy. A 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 the value chain context. The framework applied to two Italian building-integrated photovoltaic (BIPV) small-medium enterprises (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 one, three, and four actions and 82% for priority two actions, validating framework robustness. The framework provides empirical evidence for augmentation-not-automation in AI-assisted strategic planning, contributing a replicable methodology for responsible LLM integration across manufacturing sectors. Results demonstrate that combining AI synthesis efficiency with human contextual judgment enable 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)

Academic Editor: Aliakbar Kamari

Received: 17 February 2026
Revised: 28 April 2026
Accepted: 30 April 2026
Published: 8 May 2026

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1. Introduction

The European Union's Ecodesign for Sustainable Products Regulation (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 for photovoltaic (PV) module recycling, achieving 85% recovery rates under the 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 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) a regulatory urgency disconnect with environmental assessment tools quantify impacts, but do not prioritize actions based on mandatory compliance deadlines versus voluntary improvements; (ii) a 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) a lack 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 an Artificial Intelligence (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, and 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 [1] 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 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. In this study, the implementation setting is BIPV manufacturing SMEs, which currently dominate the European market in terms of the number of actors and niche, project-based production [15]. This industrial structure implies limited in-house sustainability staff and constrained budgets for LCA/LCC, making lightweight workshop-based decision tools particularly relevant. For large enterprises, the main boundary condition is not methodological but organizational: corporates with dedicated sustainability departments have established quantitative pipelines that can generate detailed environmental and financial assessments. In these settings, the LLM-MCDA-AHP framework can be used as an upstream alignment tool but will typically be integrated into existing decision architectures rather than replacing them. 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 that 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 [16–19]. Three evaluation criteria were selected based on the feasibility–desirability–viability (F-D-A) scorecard framework, adapted from the design thinking methodology [20]:
    - 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 near-zero energy building (nZEB), zero energy building (ZEB), and positive energy building (PEB) requirements [21]. Economic affordability estimates were based on industry benchmarks implementations, also including building product manufacturing, acknowledging these as practitioner estimates rather than empirically validated cost data [22–24]. Using return on investment (ROI) as the primary basis for the scoring process and product improvement projects is justified because manufacturing firms are expected to make financially efficient, benefit-driven decisions on process improvement investments. Each criterion was assessed on a 5-point Likert scale (1 = lowest, 5 = highest) [25] as described in 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 are determined through structured interviews with company leadership actors using AHP [26] pairwise comparison matrices with numbers 1, 3, 5, and 9; 1/3, 1/5, 1/9 are 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 vice versa, "1/9" indicates the first criterion is extremely less important than the second. The 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, the maximum eigenvalue of the pairwise comparison matrix (λmax), consistency index (CI), and consistency ratio (CR) were calculated for each company's AHP weighting matrix following Saaty's methodology [26,27]. 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 are analyzed to check the consistency of AHP for the use cases.

- Ecodesign actions identification. Ecodesign actions were systematically identified across 16 ESPR goal categories [1]. Each action was mapped to specific lifecycle stages (design, manufacturing, use, end-of-life) following ISO 14040 lifecycle assessment principles [28]. 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): the LLM-powered analysis used 16 ESPR goal categories and Claude 4.5 Sonnet, Anthropic [29] to scout peer-reviewed

publications on BIPV circularity, building product ecodesign, and ESPR compliance strategies with references to documents and reports (detailed prompt documentation provided in Appendix B); (2) analysis of ESPR 2024/1781 annex V requirements: these were 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) practitioner evaluation: 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 validation: 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. (Table 2) Actions were classified using a hybrid approach combining MoSCoW prioritization (must-have, should-have, could-have, won't-have) [30] with urgency–importance matrix analysis [31]. MoSCoW was selected over alternative prioritization frameworks (e.g., Kano model, RICE scoring) due to its (a) widespread adoption in project management [32]; (b) explicit time-horizon mapping (must/should/could/won't in 0–12/12–24/24–36/>36 months) aligning with ESPR compliance deadlines; and (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
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

1. Case study 1—BIPV-IGU manufacturer Glass to Power S.p.A. (G2P), Italy [33] (Figure 1). 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 [34], architectural glazing contractors, and design-build firms for commercial/institutional projects.



Figure 1. BIPV-IGU modules by Glass to Power [35].

2. Case study 2—BIPV curtain wall façade system manufacturer Gualini S.r.l. (GUA), Italy [34] (Figure 2). 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 esthetics. Gualini's BIPV façade integrates G2P's BIPV-IGU modules (or competitor 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 [34].

- Sensitivity analysis. To assess the robustness of prioritization outcomes to AHP weight variations, sensitivity analysis was conducted following standard MCDA practice [36]. Each criterion weight was varied by ±10% from its baseline value, with compensatory adjustments to other criteria maintaining the 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.
- Framework definition (Figure 3). The framework comprises sequential phases integrating LLM-assisted action identification (Phase 1) with human expert validation (Phase 2), pilot workshop refinement and strategic weighting (Phase 3), and calculated priority classification (Phase 4). Strategic alignment is achieved through C-level AHP weighting, defining business priorities, and MoSCoW classification mapping actions to implementation timeframes. Framework outputs provide a business-aligned ESPR compliance roadmap with prioritized action sequences.

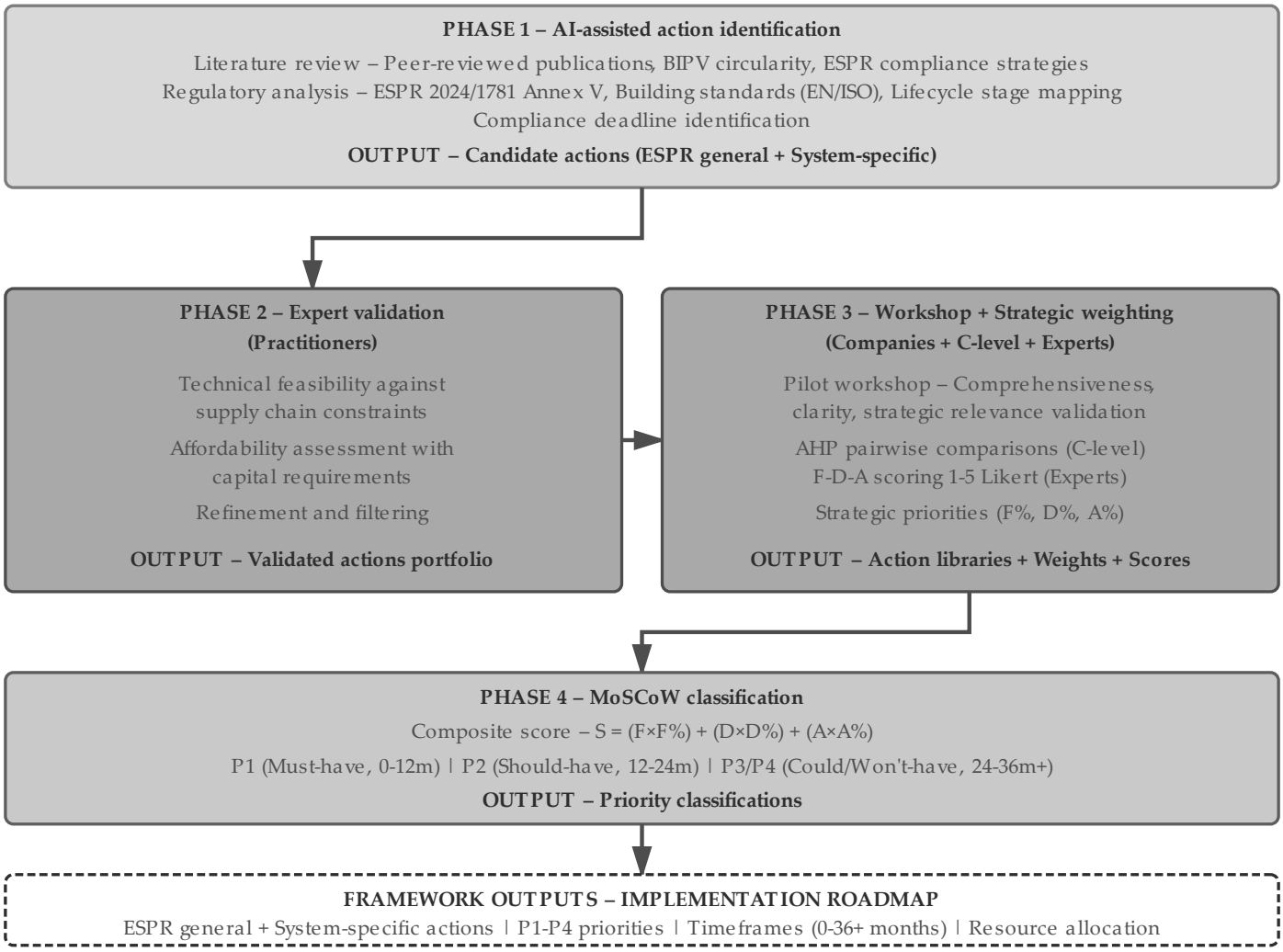

Figure 3. BIPV ecodesign prioritization framework methodology. Legend: ▭ LLM activity (Claude 4.5 Sonnet); ▭ human activity; ▭ process/calculation input/output.

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 relying on single-rate assessment (CEO for G2P and commercial director for Gualini); this single evaluation could introduce a potential individual bias, but was considered a minor shortcoming for framework application validation. The results, validated for logical consistency, show markedly different weighting profiles (Table 3).

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 the 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. This reflects a rational strategic orientation for an innovation-focused company where customer confidence in novel building products determines market penetration success. Furthermore, the low CR (2.51%) validates that these strategic judgments were internally consistent; 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's AHP profile, affordability emerged as the dominant criterion at 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 to be 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 are systematically elevated in priority relative to actions with primarily regulatory or reputational value.

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

3.2. 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..

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 projects convenient for rail transport, while G2P has smaller projects at a national scale that are difficult to optimize for rail 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 a 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.

3.3. 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).

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%
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 a 3-year horizon, given current technical and economic constraints.

Analysis of P1 actions across ESPR Annex V goal categories (Tables 5 and 6) reveals consistent prioritization patterns reflecting regulatory urgency and market imperatives for BIPV manufacturers.

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.

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

Table 6. Selected common actions demonstrating AHP-driven prioritization variation (positive variation ↑ or negative 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 aluminum (<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 aluminum (≥75%) from suppliers	3.81	3.37	0.45	↑1 level
C15	Obtain EPD certification (EN 15804+A2) [37] 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
C28	Establish 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 aluminum (water stewardship criteria)	3.50	3.85	−0.34	Same

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. 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 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 that 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: "#" number of actions.

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 the 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, the chi-square test of independence [38] 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 χ^2 value demonstrates that the framework produces regulation-aligned prioritization appropriate for compliance contexts [39], where institutional coercive pressures create isomorphic organizational responses to mandatory requirements. Strategic differentiation manifests at the action–composition level rather than aggregate distribution patterns [40]. G2P's P1 portfolio emphasizes market credentials (C15 EPD certification, C17 DPP implementation per ESPR Art. 9–13), while GUA's portfolio emphasizes cost-optimization (C3 transport logistics, C22 nesting efficiency), reflecting respective AHP weighting priorities (desirability 66% vs. affordability 63%.

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 five-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; however, it lacks quantitative rigor for boundary-sensitive actions (4.9% of portfolio). This is particularly relevant when moving beyond the utilization of LLM-generated intervention without a 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, esthetic 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 [41]. 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 [42] 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 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 [39] with mandatory compliance driving organizational change, on the other hand, 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.

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 through a framework that enables rapid ESPR prioritization. The application of this model could open a new service model to transform ESPR compliance uncertainty into actionable roadmaps within one 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 generating 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 the (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.

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 [43,44] would transform subjective affordability assessments into empirical Net Present Value (NPV) calculations with confidence intervals; TOPSIS methodology [19] 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, and affordability do not interact) and full compensability (a high score on one criterion can offset a 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 a score S = (5 × 0.16) + (5 × 0.66) + (1 × 0.19) = 4.29 (P1 priority for G2P), despite capital budget constraints making implementation impossible. This suggests that criteria such 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.

The chi-square analysis ($\chi^2 = 1590$, $p = 0.66$) demonstrates that action origin (ESPR General vs. system-specific) does not systematically bias prioritization. However, the small sample size (two companies, 81 total actions) limits statistical power for inferential conclusions. This test provides transparency regarding priority distribution patterns rather than claiming generalizable statistical validation.

A limitation of this research is the adoption of a single-LLM validation approach. The framework employed a single LLM (Claude 4.5 Sonnet) for action identification and regulatory text synthesis, relying on human expert validation to correct hallucinated technical claims and context-blind recommendations rather than multi-LLM cross-validation. The expert override demonstrates effective human-in-the-loop error correction; this approach cannot systematically detect LLM consensus failures where multiple models might generate the same incorrect output. Alternative methodologies employing multi-LLM validation (e.g., parallel prompting of Claude, GPT-4, Gemini, with answer consolidation through voting mechanisms or confidence scoring) could reduce hallucination risk by identifying outputs where models disagree, flagging them for intensive human review. The trade-off is implementation complexity and cost: single-LLM workflows require one API subscription and simplified prompt management, while multi-LLM approaches demand parallel infrastructure, cross-model prompt adaptation, and consolidation algorithms. For SME manufacturers adopting this framework, the single-LLM approach prioritizes accessibility over maximum validation rigor, accepting that expert domain knowledge (supply chain constraints, cost realities, regulatory deadlines) provides sufficient hallucination detection for business-critical decisions. Future research should empirically compare single-LLM with human validation versus multi-LLM consolidation approaches, measuring error rates, implementation time, and cost-effectiveness to establish whether added complexity delivers proportional accuracy gains for ecodesign prioritization contexts.

Another limitation is that the LLM-assisted literature review (Phase 1) was constrained to open-access publications, regulatory texts, and publicly available technical standards, as Claude 4.5 Sonnet lacks access to paywalled academic databases or at least to full papers and their insights. This limitation may have excluded relevant research published in subscription-based journals, though the framework's regulatory alignment was ensured through direct analysis of official ESPR 2024/1781 documentation and publicly accessible ISO/EN standards. Future iterations could integrate institutional database access to expand literature coverage.

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 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, 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, such as CEO, technical director, and sustainability manager) with inter-rater reliability testing, 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 being 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 the MCDA-LCA integration pilot, where high-priority actions (P1–P2 from the 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.

A comparative positioning of MCDA-AHP results versus quantitative assessment tools has been conducted based on empirical and review evidence (Table 9). The integration of LLMs specifically accelerated action identification from 6 to 12 weeks (traditional consultant-led regulatory analysis) to 2 weeks (AI synthesis and expert validation), enabling workshop-ready ESPR action libraries that eliminate preparatory education phases. The framework's rapid implementation timeline (4–6 h workshop-based prioritization within 2 weeks of comprehensive ecodesign actions definition activities) addresses a specific decision-making need: enabling C-level executives to establish strategic vision and resource allocation priorities for ESPR compliance without requiring specialized environmental expertise or lengthy data collection. This positions MCDA-AHP as complementary to, rather than competitive with, quantitative assessment tools. For the purpose of the presented framework, time and cost advantages are substantiated, positioning MCDA-AHP as a strategic filter for ESPR's actions before targeted LCA/LCC validation. It is important in this discussion to underline that the MCDA-AHP framework derives from fundamentally different objectives than the other tools. LCA quantifies environmental impacts with scientific precision suitable for regulatory submission and carbon accounting, requiring detailed product-level data (bill of materials, supplier locations, transport modes, energy consumption profiles) often unavailable at early strategy stages. The MCDA-AHP framework instead prioritizes actions using qualitative business criteria (feasibility, desirability, affordability) accessible through operational knowledge, enabling rapid consensus-building among leadership on what to do first without environmental expertise prerequisites. Traditional approaches force manufacturers into a paradox: comprehensive LCA provides quantitative rigor but requires weeks and thousands of euros of investment for each action before executives can decide which interventions merit further analysis and development. The MCDA-AHP framework supports this by enabling rapid P1–P2 identification (4–6 h, €3–5K), allowing companies to allocate detailed LCA/LCC resources selectively to high-priority actions rather than attempting a comprehensive assessment across all 40+ ESPR intervention candidates. As a consequence, the framework thus functions as a strategic filter rather than a replacement for quantitative tools.

Table 9. Decision-support tool comparison for ESPR compliance planning.

Tool/Method	Time	Cost (EUR)	Required Expertise	Primary Output	Use Case	Decision-Maker Level
LLM-MCDA-AHP (This Study)	4–6 h (1-day workshop) + 2 weeks	€3–5k (facilitated) €0 (self)	CEO, technical managers	Roadmap (0–36 months)	Prioritization and sequencing	C-level/Strategic
Simplified LCA Tools (One Click LCA, Tally)	2–4 weeks	€3k–15k	Environmental specialist or LCA-trained sustainability manager	Quantified carbon footprint (kg CO_2e) Embodied energy (MJ) EPD-compliant results	Product LCA for EPDs, green building credits for single products/processes	Technical/Compliance
LCA (ISO 14040) [28]	6–12 weeks	€5k–30k	Professional LCA practitioner	Full multi-impact profile, scenarios	Redesign, supplier comparison, regulatory dossiers for single products/processes	Technical/R&D

Life Cycle Costing (LCC) (ISO 15686-5) [44]	3–6 weeks	€4k–28k	Financial analyst, technical input	Net Present Value (NPV) Total Cost of Ownership (TCO) Payback period ROI	CAPEX decisions and business cases for single products/processes	Financial/Investment Committee
TOPSIS Multi-Criteria	1–2 weeks	€4k–10k	MCDA specialist	Ranking vs. ideal solution, sensitivity	Complex trade-offs (e.g., supplier or technology selection) for single products/processes	Technical/Procurement

An example supports this methodology, and consequently, Glass to Power's MCDA-AHP identified 15 P1 actions requiring 0–12 month implementation; the company subsequently commissioned detailed LCA for the top 3 capital-intensive interventions (low-carbon aluminum sourcing C2, PV efficiency optimization G2P4, mechanical IGU assembly G2P6) to validate ROI before finalizing supplier contracts, while implementing lower-cost P1 actions (renewable energy procurement C4, DPP data structure C17) based on qualitative assessment alone. This two-stage approach—qualitative MCDA for portfolio scoping, quantitative validation for boundary cases—achieved 60–80% faster time-to-decision while maintaining analytical rigor for high-stakes investments. This time–cost-expertise trade-off reveals why multiple methodologies must coexist in the ESPR compliance toolkit. For SME manufacturers with limited sustainability budgets, allocating resources to a single comprehensive LCA leaves insufficient capital for implementation. The MCDA-AHP framework's investment preserves capital for actual ecodesign interventions while providing sufficient strategic clarity to sequence investments rationally. For larger organizations with dedicated sustainability departments, the framework accelerates internal alignment: rather than technical specialists presenting LCA reports to executives who lack environmental expertise to interpret findings, MCDA-AHP workshops engage C-level directly in priority-setting using business language (market positioning, cost competitiveness, regulatory urgency), with LCA subsequently validating selected pathways. This comparative analysis also clarifies why TOPSIS and LCC address different decision contexts. TOPSIS excels when trade-offs involve conflicting criteria with no dominant solution, whereas MCDA-AHP's three-criterion structure (F-D-A) intentionally simplifies to maintain C-level accessibility. LCC provides investment-grade financial rigor for capital expenditure committees evaluating multi-million-Euro decisions requiring NPV calculations and risk-adjusted discount rates, whereas MCDA-AHP's affordability criterion uses qualitative assessment (A = 1–5 Likert scale) sufficient for early-stage feasibility screening. The methodologies occupy distinct decision-support niches rather than competing for the same use case.

The framework does not include comparative validation against human-consultant-generated baseline action portfolios. No independent ESPR action library for BIPV existed at study commencement, and parallel consultant engagement would have required additional budget (Table 9) beyond the proof-of-concept research scope. LLM contribution is demonstrated through (1) a 6–8 week time reduction versus traditional regulatory analysis, (2) a systematic coverage of all 16 ESPR Annex V categories, and (3) an expert validation retention rate (overall 30 and 10/11 AI-generated candidates deemed technically feasible and regulatorily aligned by 5 practitioners). Future research could conduct controlled studies comparing parallel teams generating portfolios with/without LLM assistance, measuring coverage completeness, technical accuracy, and cost-effectiveness.

5. Conclusions

The proposed framework can address 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 LLM-identified interventions, validating the hybrid human–AI methodology. This positions the framework as a 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. 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 provides rapid, actionable prioritization for manufacturers lacking resources for comprehensive LCA or circularity assessment. While simplified LCA tools (e.g., One Click LCA [45], Tally [46]) 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 into business decisions. The MCDA-AHP framework complements these tools by enabling rapid strategic prioritization (4–6 h) using operational knowledge (supplier availability, production constraints) accessible to CEOs/technical managers, without requiring environmental expertise. 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 operationalizes strategic vision through weighted criteria, translating abstract sustainability commitments into concrete action sequences coherent with competitive positioning. 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, which allows SMEs to sequence investments strategically rather than attempting simultaneous implementation, which would exceed financial and organizational capacity.

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, provided that differentiation reflects strategic positioning rather than arbitrary prioritization. For BIPV manufacturers navigating ESPR compliance, the MCDA-AHP framework can offer a practical, accessible tool for addressing the prioritization of LLM-driven actions and supporting 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) under Grant Agreement No. 101096139. However, views and opinions expressed are 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: All data generated during this study are included in this published article and its Appendix. The complete ecodesign action matrices for both case study companies (Glass to Power and Gualini), including Feasibility-Desirability-Affordability scores, AHP weighting profiles, priority classifications, and supporting references, are presented in Appendix A (Tables A1 and A2). No additional datasets were generated or analyzed beyond those presented in the manuscript.

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 decision-makers for framework validation workshops. During the preparation of this study, the authors used Claude 4.5 Sonnet (Anthropic) for (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 were employed by Levery s.r.l. società benefit. The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results. 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	Aluminum 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	Positive-Energy Building
PV	Photovoltaic
PV-IGU	Photovoltaic Insulated Glazing Unit
ROI	Return on Investment
SME	Small and Medium-Sized Enterprise
SVHC	Substances of Very High Concern
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
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 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	[37,47,48]
C2	Carbon footprint	Manufacturing	ESPR General	Source low-carbon/local aluminum (<4 kg CO_2e/kg) from suppliers	5	5	3	4.63	P1	[37,49,50]
C3	Carbon footprint	Manufacturing	ESPR General	Optimize transport mode selection (rail/truck) based on distance	2	3	2	2.66	P4	[37,51,52]
C4	Carbon footprint	Manufacturing	ESPR General	Source from suppliers with renewable energy credentials	3	4	3	3.66	P2	[53–55]
G2P1	Carbon footprint	Manufacturing	System-Specific (G2P Assembly)	Transition to 100% renewable energy for assembly facility	5	4	5	4.34	P1	[53–55]
C5	Durability	Design	ESPR General	Declare and extend warranty period (target 10–15 years)	4	5	3	4.47	P1	[56–58]
G2P2	Durability	Design	System-Specific (IGU)	Optimize thermal break design in IGU spacer system	5	4	2	3.78	P2	[59,60]
G2P3	Durability	Design	System-Specific (IGU)	Enhanced climate protection (tempered/laminated glass)	5	4	4	4.16	P1	[61–63]
C6	Energy	Manufacturing	ESPR General	Source low-embodied energy materials from supply chain	3	5	3	4.31	P1	[49,64,65]
G2P4	Energy	Use	System-Specific (PV)	Optimize PV cell arrangement for electrical efficiency	4	4	4	4.00	P1	[58,66]
C7	Maintenance	Design	ESPR General	Design for inspectability at critical points	4	5	4	4.66	P1	[67,68]
C8	Maintenance	Use	ESPR General	Integrate IoT remote monitoring system	4	3	3	3.16	P3	[69–71]
G2P5	Maintenance	Use	System-Specific (PV)	Establish preventive maintenance protocols for PV-IGU	5	4	4	4.16	P1	[71–73]
C9	Recoverability	End of Life	ESPR General	Document disassembly sequence in DPP	4	3	4	3.34	P3	[1,74,75]
C10	Recoverability	End of Life	ESPR General	Partner with glass recyclers for closed-loop recovery	3	3	2	2.81	P4	[76–78]
C11	Recoverability	End of Life	ESPR General	Establish WEEE-compliant take-back program	2	4	2	3.31	P3	[79–81]
C12	Recyclability	Design	ESPR General	Create material passport for DPP (materials inventory)	4	3	4	3.34	P3	[82–84]
C13	Recyclability	Design	ESPR General	Design dry fastening connections, eliminate permanent adhesives	3	3	3	3.00	P3	[75,85,86]
G2P6	Recyclability	Design	System-Specific (IGU)	Replace butyl sealant with mechanical/velcro-type connections for IGU assembly	2	2	2	2.00	P4	[87,88]
G2P7	Recyclability	Design	System-Specific (IGU)	Switch to low-VOC/certified structural silicone (avoiding non-recyclable sealants)	4	3	3	3.16	P3	[89,90]

C14	Recycled	Manufacturing	ESPR General	Source high recycled aluminum (≥75%) from suppliers	4	4	3	3.81	P2	[91–93]
G2P8	Recycled	Manufacturing	System-Specific (IGU)	Source glass with 40–60% recycled cullet from suppliers	3	3	3	3.00	P3	[94–96]
G2P9	Recycled	Manufacturing	System-Specific (IGU)	Source spacer bars with recycled content from suppliers	3	2	2	2.16	P4	[37,97,98]
C15	Reliability	Manufacturing	ESPR General	Obtain EPD certification (EN 15804+A2) for product	5	5	3	4.63	P1	[1,37,45]
C16	Reliability	Manufacturing	ESPR General	Implement quality control labeling (CE marking per CPR)	5	5	4	4.81	P1	[99–101]
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	[88,102,103]
C17	Repairability	Manufacturing and Use	ESPR General	Implement DPP system per ESPR Art. 9–13	4	5	3	4.47	P1	[1,104,105]
C18	Repairability	Use	ESPR General	Publish repair/maintenance documentation via DPP	5	4	5	4.34	P1	[1,71]
C19	Repairability	Design	ESPR General	Design accessible junction boxes/electrical connections	4	4	5	4.19	P1	[106–108]
C20	Repairability	Design	ESPR General	Provide 3D models/digital twins for replaceable components	3	2	4	2.53	P4	[109–111]
C21	Resource	Design	ESPR General	Optimize component-to-frame ratio for material efficiency	4	3	4	3.34	P3	[67,112]
C22	Resource	Manufacturing	ESPR General	Implement nesting optimization, reduce scrap during cutting/machining	4	3	4	3.34	P3	[113–115]
C23	Reusability	Design	ESPR General	Standardize components across product variants (modular design)	5	3	4	3.50	P2	[116–118]
G2P11	Reusability	Design	System-Specific (IGU/PV)	Standardize PV frame components (junction boxes, cable glands, mounting pins)	5	3	4	3.50	P2	[119,120]
C24	Substances	Manufacturing	ESPR General	Source materials with VOC-free/low-VOC certifications from suppliers	5	4	4	4.16	P1	[89,121,122]
C25	Substances	Manufacturing	ESPR General	Document SVHC substances in DPP per ESPR Art. 7(5)	4	3	4	3.34	P3	[123–125]
C26	Upgradability	Design	ESPR General	Design modular electrical connections for future component upgrades	3	4	3	3.66	P2	[62]
C27	Waste	Manufacturing	ESPR General	Implement scrap recovery systems (Al to remelting, glass cullet return)	4	3	4	3.34	P3	[4,93,114]
C28	Waste	Manufacturing	ESPR General	Zero-waste-to-landfill target for manufacturing operations	3	3	3	3.00	P3	[114,126,127]
C29	Waste	End of Life	ESPR General	Design for selective demolition and component separation	3	3	3	3.00	P3	[75,128,129]

C30	Water	Manufacturing	ESPR General	Source ASI-certified aluminum (water stewardship criteria)	5	3	4	3.50 P2	[92,130,131]

Table A2. Gualini 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	4.26	P1	[37,47,48]
C2	Carbon footprint	Manufacturing	ESPR General	Source low-carbon/local aluminum (<4 kg CO_2e/kg) from suppliers	5	5	3	3.73	P2	[37,49,50]
C3	Carbon footprint	Manufacturing	ESPR General	Optimize transport mode selection (rail/truck) based on distance	4	4	5	4.63	P1	[37,51,52]
C4	Carbon footprint	Manufacturing	ESPR General	Source from suppliers with renewable energy credentials	3	4	3	3.26	P3	[53–55]
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	[53–55]
C5	Durability	Design	ESPR General	Declare and extend warranty period (target 10–15 years)	4	5	3	3.63	P2	[56–58]
GUA2	Durability	Design	System-Specific (Façade)	Design polymer thermal break profiles for disassembly in façade frames	3	3	3	3.00	P3	[132,133]
C6	Energy	Manufacturing	ESPR General	Source low-embodied energy materials from supply chain	4	4	3	3.37	P3	[49,64,65]
C7	Maintenance	Design	ESPR General	Design for inspectability at critical points	4	5	4	4.26	P1	[67,68]
C8	Maintenance	Use	ESPR General	Integrate IoT remote monitoring system	4	3	3	3.11	P3	[69–71]
GUA3	Maintenance	Use	System-Specific (Façade)	Establish preventive maintenance service contracts with remote diagnostics for façade-integrated BIPV	5	3	3	3.21	P3	[134–136]
C9	Recoverability	End of Life	ESPR General	Document disassembly sequence in DPP	4	3	4	3.74	P2	[1,74,75]
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	[94–96]
C10	Recoverability	End of Life	ESPR General	Partner with glass recyclers for closed-loop recovery	3	3	2	2.37	P4	[76–78]
C11	Recoverability	End of Life	ESPR General	Establish WEEE-compliant take-back program	2	4	2	2.52	P4	[79–81]

GUA5	Recoverability	End of Life	System-Specific (Façade)	Partner with aluminum remelting facilities for closed-loop façade frame recovery	5	3	4	3.85 P2	[137–139]
C12	Recyclability	Design	ESPR General	Create material passport for DPP (materials inventory)	4	3	4	3.74 P2	[82–84]
C13	Recyclability	Design	ESPR General	Design dry fastening connections, eliminate permanent adhesives	3	3	3	3.00 P3	[75,85,86]
GUA6	Recyclability	Design	System-Specific (Façade)	Replace EPDM gaskets with thermoplastic elastomer (TPE) for façade sealing	2	2	3	2.63 P4	[140,141]
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	[142–144]
C14	Recycled	Manufacturing	ESPR General	Source high recycled aluminum (≥75%) from suppliers	4	4	3	3.37 P3	[91–93]
C15	Reliability	Manufacturing	ESPR General	Obtain EPD certification (EN 15804+A2) for product	4	5	3	3.63 P2	[1,37,45]
C16	Reliability	Manufacturing	ESPR General	Implement quality control labeling (CE marking per CPR)	5	5	4	4.37 P1	[99–101,145]
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	[65,130]
C17	Repairability	Manufacturing and Use	ESPR General	Implement DPP system per ESPR Art. 9–13	3	5	3	3.52 P2	[1,104,105]
C18	Repairability	Use	ESPR General	Publish repair/maintenance documentation via DPP	5	4	5	4.74 P1	[1,71]
C19	Repairability	Design	ESPR General	Design accessible junction boxes/electrical connections	4	4	5	4.63 P1	[106–108]
GUA9	Repairability	Design	System-Specific (Façade)	Use corrugated conduit with snap-fit cable routing (no permanent installation)	5	4	5	4.74 P1	[146–148]
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	[149–151]
C20	Repairability	Design	ESPR General	Provide 3D models/digital twins for replaceable components	3	2	4	3.37 P3	[109–111]
C21	Resource	Design	ESPR General	Optimize component-to-frame ratio for material efficiency	4	3	4	3.74 P2	[67,112]
C22	Resource	Manufacturing	ESPR General	Implement nesting optimization, reduce scrap during cutting/machining	5	4	4	4.11 P1	[113–115]
C23	Reusability	Design	ESPR General	Standardize components across product variants (modular design)	5	4	4	4.11 P1	[116–118]

C24	Substances	Manufacturing	ESPR General	Source materials with VOC-free/low-VOC certifications from suppliers	5	5	4	4.37 P1	[89,121,122]
C25	Substances	Manufacturing	ESPR General	Document SVHC substances in DPP per ESPR Art. 7(5)	4	4	4	4.00 P1	[123–125]
C26	Upgradability	Design	ESPR General	Design modular electrical connections for future component upgrades	3	4	3	3.26 P3	[62]
C27	Waste	Manufacturing	ESPR General	Implement scrap recovery systems (Al to remelting, glass cullet return)	4	3	4	3.74 P2	[4,93,114]
C28	Waste	Manufacturing	ESPR General	Zero-waste-to-landfill target for manufacturing operations	3	3	3	3.00 P3	[114,126,127]
C29	Waste	End of Life	ESPR General	Design for selective demolition and component separation	3	3	3	3.00 P3	[75,128,129]
C30	Water	Manufacturing	ESPR General	Source ASI-certified aluminum (water stewardship criteria)	5	3	4	3.85 P2	[92,130,131]

Appendix B. LLM Prompt for BIPV Ecodesign Action Identification

This appendix documents the LLM prompts and human validation protocols used in Stages 1–2 of the methodology (Section 2) to ensure full transparency and enable independent replication of the AI-assisted action identification process. The appendix provides: (1) the complete verbatim prompt used for ESPR General and system-specific action generation, (2) iteration details and output quantities, (3) expert validation workflow, and (4) refinement outcomes.

Appendix B.1. LLM Tool Specification

Model: Claude 4.5 Sonnet (Anthropic, October 2024 version).
Access Method: Web interface (Claude.ai).
Primary Use: Literature synthesis, regulatory text analysis, and structured action portfolio generation.
Temperature/Settings: Default configuration (no custom parameter modifications).

Appendix B.2. Action Identification Prompt

The following prompt was used to generate both ESPR General actions (applicable across all BIPV manufacturers) and system-specific actions (context-dependent interventions tailored to manufacturing stage and product type). The prompt was executed separately for each case study company with company-specific input parameters.

Prompt text (verbatim):

CONTEXT:

You are an expert in Building-Integrated Photovoltaics (BIPV) manufacturing, circular economy, and EU ecodesign regulations. You will help identify ecodesign actions for BIPV manufacturers to comply with the European Ecodesign for Sustainable Products Regulation (ESPR 2024/1781, Annex V).

Your task is to generate a comprehensive list of ecodesign actions classified into:

1. ESPR General actions—regulatory-mandated interventions applicable across all BIPV manufacturers

2. System-specific actions—context-dependent interventions tailored to specific manufacturing stages or product types

INPUT INFORMATION:

- Company Type: [PV-IGU component manufacturer/BIPV façade system integrator]
- Product Description:
  - Main product: [Glass-to-glass PV modules with aluminum frames integrated into insulated glazing units/Prefabricated BIPV curtain wall systems]
  - Key materials: [Low-iron glass, monocrystalline silicon PV cells, aluminum extrusions, butyl sealant, structural silicone/Aluminum framing systems, IGU components, electrical conduits, junction boxes]
  - Manufacturing process: [Lamination, IGU assembly, electrical integration, quality testing/Off-site prefabrication, system integration, on-site installation coordination]
  - Supply chain position: [Component supplier to façade manufacturers/System integrator working with component suppliers and installers]

TASK INSTRUCTIONS:

Step 1: Generate ESPR General Actions (Target: 30 actions)

For each of the following ESPR 2024/1781 Annex V goal categories, identify regulatory-mandated interventions applicable to ANY BIPV manufacturer:

1. Carbon footprint
2. Durability
3. Energy use and efficiency
4. Maintenance and refurbishment
5. Recoverability
6. Recyclability
7. Recycled content
8. Reliability
9. Remanufacturability
10. Repairability
11. Resource use efficiency
12. Reusability
13. Substances of concern
14. Upgradability
15. Waste generation
16. Water use and efficiency

For each action, provide:

- Action ID: C1, C2, C3… (Common actions applicable across manufacturers)
- Goal Category: From ESPR Annex V list above
- Lifecycle Stage: Design/Manufacturing/Use/End of Life/All stages
- Action Description: Clear, concise statement (e.g., "Develop verified Product Carbon Footprint (PCF) for Digital Product Passport per ESPR Art. 7")
- References: 2–3 authoritative sources (ISO standards, peer-reviewed publications with DOI, EU regulations, industry guidelines from IEA PVPS, European Aluminium, Glass for Europe)

Step 2: Generate System-Specific Actions (Target: 10–15 actions)

Based on the company-specific context provided, identify interventions that are:

- Unique to the manufacturing stage (component-level vs. system-level)
- Product-specific (IGU cavity management for component manufacturers/façade electrical integration for system integrators)

- Supply chain position-dependent (upstream material sourcing vs. downstream installation coordination)

For each system-specific action, provide:

- Action ID: [Company Code]1, [Company Code]2… (e.g., G2P1, GUA1)
- Goal Category: From ESPR Annex V
- Lifecycle Stage: Specify
- Action Description: Context-specific intervention explaining why it is unique to this manufacturing stage or product type
- References: Technical sources, case studies, supplier solutions, research publications

QUALITY CRITERIA:

- Comprehensiveness: All 16 ESPR Annex V categories covered in ESPR General actions
- Specificity: Actions are concrete, implementable interventions (not vague sustainability principles)
- Regulatory Alignment: Direct references to ESPR 2024/1781, CPR 305/2011, WEEE 2012/19/EU, REACH, where applicable
- Actionability: Each action includes 2–3 authoritative references with hyperlinks where possible
- Differentiation: Clear distinction between ESPR General (cross-manufacturer applicability) vs. system-specific (context-dependent, non-transferable to other supply chain positions)

ADDITIONAL INSTRUCTIONS:

- Prioritize MANDATORY regulatory actions in ESPR General category (Digital Product Passport implementation, Environmental Product Declaration per EN 15804+A2, CE marking per CPR 305/2011, SVHC documentation per REACH/SCIP database)
- Include implementation timeline hints where relevant (e.g., "DPP mandatory 2026–2027" or "EPD increasingly required for public procurement")
- Flag interdependencies between actions where one action is a prerequisite for another
- Highlight supply chain coordination needs (e.g., "Requires aluminum supplier renewable energy data")
- Focus on EU regulatory context (ESPR, REACH, WEEE, CPR)
- BIPV specificity required—actions must reflect glass-aluminum-PV material combinations and building integration constraints, not generic photovoltaic modules
- Manufacturing stage differentiation—component suppliers vs. system integrators have different circular economy leverage points (material-level vs. assembly-level)
- Avoid generic sustainability advice—every action must be implementable within 0–36 months using existing or near-term commercially available technologies
- Reference quality matters—prioritize ISO/EN standards, peer-reviewed DOI publications, EU Official Journal regulations, established industry organizations (IEA PVPS Task 13/15, European Aluminium, Glass for Europe)

VALIDATION CHECKLIST:
Before finalizing output, verify:

- All 16 ESPR Annex V goal categories represented in ESPR General actions
- Each action includes 2–3 authoritative references
- System-specific actions are genuinely non-applicable to other supply chain positions (justify why component-level vs. system-level distinction matters)
- Actions are specific interventions with clear implementation paths, not vague principles

- Regulatory deadlines mentioned where relevant (DPP 2026–2027, EPD market requirements, WEEE compliance)
- Lifecycle stages correctly assigned (Design/Manufacturing/Use/End of Life)

Appendix B.3. Implementation Details

Stage 1: ESPR General Actions (common to both companies)

- Iterations: 3 LLM prompt executions.
  - Iteration 1: Initial generation based on ESPR 2024/1781 Annex V goal categories.
  - Iteration 2: Regulatory alignment refinement (cross-reference with EN 15804+A2, CPR 305/2011, WEEE 2012/19/EU).
  - Iteration 3: Reference validation and lifecycle stage verification.
- Output: 42 candidate ESPR General actions.
- Expert refinement: Authors and 5 BIPV industry practitioners reviewed candidates, eliminating redundancies and merging overlapping interventions.
- Final Output: 30 ESPR General actions (C1–C30).

Stage 2: System-Specific Actions (company-dependent)

- Glass to Power (G2P)—BIPV-IGU Component Manufacturer:
  - Iterations: 2 LLM prompt executions with company-specific technical documentation.
  - Output: 18 candidate system-specific actions.
  - Expert Refinement: filtered to 12 actions (G2P1–G2P12).
- GUALINI—BIPV Façade System Integrator:
  - Iterations: 2 LLM prompt executions with company-specific operational context.
  - Output: 15 candidate system-specific actions.
  - Expert Refinement: Filtered to 10 actions (GUA1–GUA10).

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