

Article

Prefabricated Solutions for Energy-Saving Renovation: A Technology Supply Mapping of Southern European Cases

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Abstract

To achieve the European Union's zero-emission building targets and overcome the limitations of slow, costly on-site construction, off-site prefabrication is vital. However, existing research often neglects real-world constructability and circularity constraints. This study presents a systematic technology supply mapping and a performance-oriented taxonomy—single-function envelopes, multi-functional integrated systems, and stand-alone installations—of prefabricated renovation solutions, focusing predominantly on Southern European contexts. Applying a structured three-step screening protocol across the literature, industry databases, and European project repositories, technologies were evaluated through a multi-dimensional framework capturing market readiness, functional integration, structural constraints, and circularity indicators. Results reveal a strongly polarized market where passive envelope systems dominate commercial availability, while multi-functional active solutions remain largely confined to experimental prototype stages. Furthermore, most systems target low-to-mid-rise residential buildings, show limited compatibility with complex architectural geometries, and exhibit low integration of circular criteria due to conventional material reliance. This study concludes that bridging the research-to-market gap requires interface standardization, demand aggregation through Green Public Procurement, and localized regulatory adaptations for envelope thickness. Ultimately, this taxonomy establishes a rigorous diagnostic framework and a solid foundation for a future quantitative Prefabrication Readiness Index (PRI).



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1. Introduction

The decarbonization of the European building stock represents one of the most pressing challenges within the European Green Deal's pathway toward climate neutrality by 2050. Buildings currently account for approximately 40% of final energy consumption and 36% of energy-related greenhouse gas (GHG) emissions within the European Union (EU),

making the construction and real-estate sectors central to the achievement of European climate objectives [1–3]. In response, the European Commission launched the Renovation Wave Strategy in 2020, establishing the objective of at least doubling the annual renovation rate by 2030 [4,5]. These ambitions were subsequently reinforced through the recast Energy Performance of Buildings Directive (Directive (EU) 2024/1275, EPBD), introducing strict mandates for zero-emission buildings, whole-life carbon assessment, and the progressive phase-out of inefficient building stocks [1,6,7]. The urgency of this shift is amplified by the state of the existing built environment: nearly 85% of European buildings were constructed before 2000 without modern thermal codes, resulting in inadequate insulation levels, obsolete technical systems, poor indoor environmental quality, and high operational energy demand [8–12].

Despite substantial financial incentives, the current annual pace of deep renovation—defined as retrofits achieving at least a 60% reduction in primary energy demand—remains stagnant at approximately 0.2% across Europe [13]. To reach the EPBD climate targets, this rate must accelerate to at least 3% annually. Conventional renovation approaches continue to rely on labor-intensive on-site construction, sequential wet-trade interventions, and fragmented subcontracting chains [14,15]. These traditional practices are inherently slow, weather-dependent, generate significant construction waste, and cause severe operational disruption to occupants, fostering low consumer adoption [16,17]. Consequently, the European renovation ecosystem remains particularly vulnerable to regulatory fragmentation, supply-chain discontinuities, financing uncertainties, and low levels of industrial coordination [18,19]. In this scenario, industrialized off-site prefabrication emerges as a strategic pathway capable of shifting operations to automated factory configurations, compressing installation timelines, and standardizing quality control [20–22].

However, the large-scale deployment of prefabricated renovation solutions faces major operational friction zones that slow down market adoption, categorized into four interconnected macro-dimensions:

1. **Regulatory and Permitting Obstacles:** Cross-border scalability is hindered by highly localized urban planning codes. For instance, external prefabricated panels typically increase wall thickness by 15 to 35 cm [23], frequently violating municipal regulations regarding property boundaries or minimum building distances in dense historic centers [17,24].
2. **Socio-Economic and Organizational Constraints:** The high upfront capital expenditure (Capex) required to establish automated manufacturing lines creates market hesitation, while traditional banking frameworks struggle to finance off-site operations where assets are generated in factories rather than on-site [14,20]. On the demand side, this market friction is heavily compounded by deep socio-organizational and governance barriers within the existing housing stock [20]. These include highly fragmented multi-family property ownership structures and complex condominium decision-making grids, where deep retrofits often require democratic voting consensus among uncooperative co-owners or multi-layered facility management structures. This creates severe split-incentive dilemmas, particularly between fixed-income elderly owners reluctant to invest long-term and short-term tenants or absent landlords focused solely on minimizing immediate maintenance costs [10,20].
3. **Human Capital and Supply Chain Fragmentation:** A critical shortage of skilled labor proficient in Digital Design for Manufacture and Assembly (DfMA) persists within a market dominated by fragmented micro-contractors operating in isolated industrial silos [20].
4. **Physical and Operational Installability Constraints:** Legacy substrates from the 1950–1980 era often feature degraded concrete or masonry with undocumented load-

bearing capacities, risking structural failure when supporting heavy panels without reinforcement [17]. Furthermore, geometric irregularities, structural out-of-plumbness, and high-altitude dynamic wind-shear profiles significantly complicate panel anchoring and tolerance absorption on-site [17,24].

A significant gap in the current literature exacerbates these barriers: existing research remains heavily fragmented, focusing almost exclusively on theoretical energy performance indicators while neglecting real-world installability, constructability risks, and circularity constraints [25]. While multi-criteria decision-making tools are frequently used to optimize specific prefabricated typologies [26], holistic frameworks simultaneously evaluating technological integration, market maturity, and circularity remain absent. This reinforces a profound “circularity paradox”; to satisfy immediate operational energy metrics, current trends rely heavily on thick layers of carbon-intensive, synthetic insulation materials (such as EPS or PIR foams), significantly inflating the embodied carbon footprint of the renovation and ignoring Design for Disassembly (DfD) principles [27–29]. To resolve this, circular economy action plans and related EU initiatives increasingly emphasize the need to reduce construction waste, extend material life cycles, and promote regenerative material loops (such as bio-based or recycled fibers) evaluated for low environmental impact [30,31], as circular strategies are vital for long-term resilience and resource efficiency [32]. Furthermore, demolition and renovation activities remain among the largest contributors to material consumption and landfill generation, making prefabrication a strategic enabler for circular construction due to its potential to minimize waste and optimize industrial resource flows [33–35].

To bridge this implementation gap, this study focuses on the physical hardware dimension of industrialized retrofitting. Embedded within the European LIFE project BARRIO (LIFE23-CET-BARRIO) [36], this paper introduces the “BARRIO | PREFAB MAPPING_X2” framework to systematically map and classify prefabricated physical solutions. Moving away from a global pan-European market analysis, which would require commercial sales volumes and demand-side data, this study is explicitly configured as a technology supply mapping. The curated dataset reflects the geographical and industrial footprint of the BARRIO project consortium, focusing predominantly on selected Southern European cases (primarily Italy and Spain) while cataloguing their technological configurations. Specifically, this study aims to answer the following research questions:

RQ1: *What is the current distribution and technology maturity level of prefabricated physical solutions within the selected Southern European market compared to conventional passive components?*

RQ2: *Which technical applicability constraints and circularity boundaries restrict the large-scale industrial deployment of these mapped solutions?*

While macro-level institutional repositories—such as the European Building Stock Observatory (BSO) or the market roadmaps published by the Buildings Performance Institute Europe (BPIE)—provide essential top-down statistical datasets, they are naturally designed for macroeconomic policy tracking rather than micro-level technology assessment. Therefore, this study does not seek to replicate those invaluable databases but rather to complement them by introducing a dedicated, engineering-oriented operational taxonomy. The unique contribution of this work lies in providing a targeted diagnostic layer that maps functional integration levels and physical deployability thresholds, adding necessary technical granularity to the existing European building renovation literature.

The remainder of this paper is structured as follows: Section 2 outlines the state of the art in industrialized prefabrication; Section 3 defines the methodology used for database population; Section 4 interprets the market mapping results and taxonomic classification;

Section 5 discusses the operational implications, while Section 6 provides concluding remarks and policy paths.

2. State of the Art: Industrialized Retrofit and Digital Enablers

2.1. Industrialized Prefabrication as a Strategic Pathway for Deep Renovation

Prefabricated renovation systems transfer a substantial portion of construction activities from the building site to controlled manufacturing environments, enabling higher quality control, shorter installation times, lower weather dependency, reduced waste production, and increased construction predictability [21,22,37]. Unlike traditional retrofit practices, industrialized renovation strategies aim to transform renovation into a semi-manufacturing process characterized by repeatability, modularity, and process optimization [38]. The structural transition from traditional on-site building practices to automated off-site manufacturing loops is schematized and visually analyzed in Figure 1.

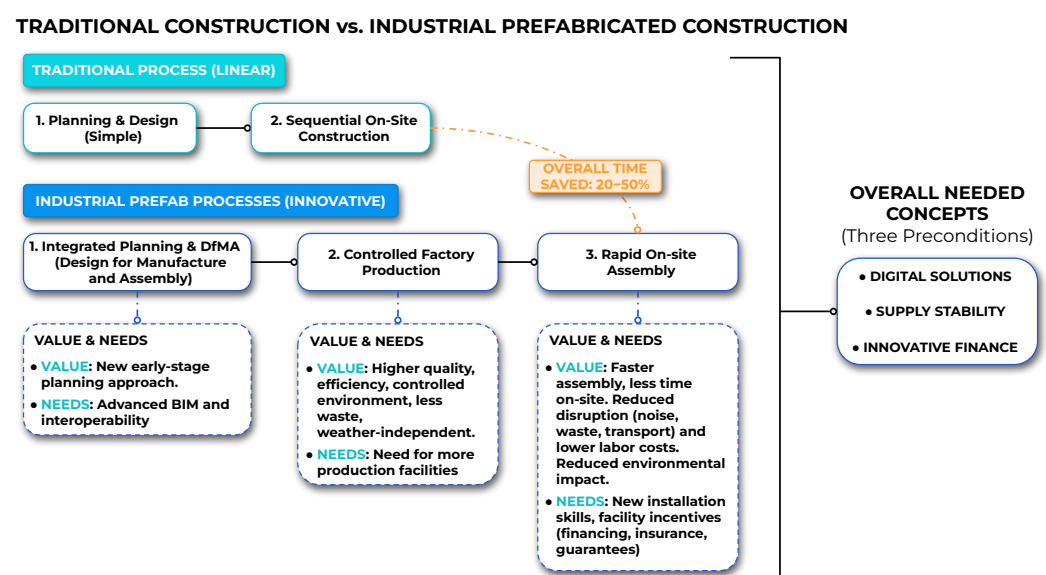


Figure 1. Conceptual workflow comparison between traditional construction and industrialized prefabrication based on the research framework. Innovation and needs: traditional construction vs. industrial prefabrication.

As conceptualized in Figure 1, shifting operations to automated factory configurations allows a significant reduction in execution times. A detailed operational assessment comparing these two structural methodologies across key project parameters is summarized in Table 1.

One of the most advanced expressions of this industrialized approach is represented by multi-functional prefabricated façade systems integrating insulation layers, airtightness membranes, pre-installed windows, ventilation systems, renewable energy technologies, and digital monitoring devices within single industrialized modules [22,39]. These technologies enable simultaneous interventions on both the building envelope and technical systems, substantially reducing installation complexity and minimizing disturbance for occupants. In several pilot demonstrations, façade modules have been installed within only a few days through crane-assisted operations, compared with weeks or months required by conventional renovation practices [40].

The Energiesprong initiative in the Netherlands represents one of the most widely recognized demonstrations of industrialized deep renovation, showing that near-net-zero retrofits can be delivered within 4–10 days through the adoption of prefabricated roof and façade modules manufactured off-site [21,41]. Similar approaches have subsequently been

explored within several European research initiatives, which investigated different forms of industrialized renovation ecosystems integrating envelope systems, HVAC technologies, renewable energy generation, and digital workflows. To contextualize the state of the art, a comprehensive cross-project analysis of these multi-national programs is detailed in Table 2.

Table 1. Structural comparison of traditional on-site renovation and off-site prefabricated solutions.

Metric/Parameter	Traditional On-Site Renovation	Off-Site Prefabricated Renovation
On-Site Execution Time	Months to years (highly intrusive) [17]	Days (typically 4–10 days per building) [17]
Precision and Tolerances	Centimeters (subject to manual error) [16]	Millimeters (typically < 1 mm in factory) [16]
Material Waste Generation	High on-site waste (up to 30% material excess) [17]	Minimized (up to 25–30% waste reduction in factory) [27]
Occupant Disruption	High (temporary relocation often required) [17]	Low (occupants can remain in situ) [17]
Weather Dependency	Extreme (subject to seasonal stoppages)	Minimal (fabrication occurs in dry, indoor settings) [17]
System Integration	Sequential, fragmented on-site installation [13]	Simultaneous, monolithic off-site assembly [13]

Table 2. Systematic mapping of major EU-funded prefabricated deep renovation projects and hardware (ST) solutions. (Data source: BARRIO database, compiled as of March 2025).

Project Acronym	Demo Countries	Primary Physical Hardware (ST) Innovations	Circularity & Materials Strategy
PLURAL [39]	Greece, Spain, Czech Republic	SmartWall steel-framed active system, ConExWall timber-framed external wall heating/cooling	98% recyclable materials, use of PCM-coatings
4RinEU [40]	Norway, Netherlands, Spain, Italy	Timber-framed prefabricated envelope panels, integrated decentralized/centralized ventilation, hydronic Energy Hub	Reusable PV-panel configurations, regional geo-cluster customization
Drive 0 [42]	Estonia, Netherlands, Italy, Spain, Ireland	Bio-based 2D façade elements, 3D modular “pod” additions	Up to 50% embodied carbon reduction, local timber frames, custom Design for Disassembly (DfD) connections
ENSNARE [43]	Bulgaria, Estonia, Italy	Modular “active façade” mesh, integrated multi-layer solar harvesting (BIPV/BIST)	Low-density insulation for on-site substrate leveling, circular envelope layering
INFINITE [29]	Italy	All-in-one timber frames, smart window kits, decentralized MVU integration	Green envelope modules with greywater treatment, bio-based timber frames
ProGETonE [44]	Italy, Greece, Romania, Netherlands	Modular CLT/steel frame external exoskeletons, physical structural added volumes	Structural–thermal integration to extend the lifespan of masonry/concrete frames
MeeFS [45]	Finland, Russia, Spain	Modular panels with integrated HVAC, active solar shading, localized ventilation ducts	Predefined dimensional standardization, highly recyclable panel sub-components
ABRACADABRA [23]	Italy, Spain	AdoRE prefabricated timber modular additions, rooftop volumetric extensions	Reversible structural attachments, timber framing to minimize added load
SINFONIA [46]	Germany, Austria, Switzerland	Prefabricated timber-framed E.T. façade system with mineral wool and integrated PV	Focus on natural, renewable timber frames, dry-joint construction

However, the transition from pilot demonstration to large-scale industrial deployment remains far from complete. While single-function façade systems and prefabricated insulation modules have progressively reached commercial maturity in several European countries, highly integrated multi-functional solutions combining envelope technologies, HVAC integration, and renewable energy systems continue to face major barriers to widespread adoption [20,22]. Recent market assessments published by BPIE [41] and Rocky Mountain Institute [47] confirm that the European market still shows a strong imbalance between commercially mature passive envelope systems and more advanced multi-functional industrialized retrofit technologies.

The reasons behind this technological gap are multi-dimensional. First, integrating HVAC systems within prefabricated façade modules introduces substantial engineering challenges associated with duct routing, condensate management, acoustic insulation, maintenance accessibility, and fire safety compliance [20]. Unlike passive envelope components, active systems require interoperability between architectural, structural, and mechanical domains, increasing both manufacturing complexity and certification requirements.

Second, the heterogeneity of the European building stock significantly limits the replicability of standardized solutions. Existing buildings frequently exhibit irregular geometries, undocumented structural conditions, façade misalignments, and inconsistent construction techniques that complicate the application of industrialized modules [45]. This issue is particularly relevant within historic urban centers, where heritage preservation constraints often restrict external over-cladding operations or visible façade transformations [24,48].

Third, the industrial ecosystem supporting prefabricated renovation remains fragmented and geographically uneven. While some countries such as Italy, Spain, Ireland, and the Netherlands have developed relatively mature prefabrication markets driven by public incentives and pilot programs, many other European regions still lack industrial capacity, standardized certification pathways, and coordinated supply chains [41]. The absence of harmonized European interoperability frameworks further limits cross-border scalability and slows down market diffusion [20,49]. Supply-chain maturity itself is increasingly recognized as a crucial determinant for the successful deployment of industrialized renovation systems [36].

2.2. Digitalization, Mass Customization, and Future of Industrialized Renovation

The growing integration of digital workflows within the construction sector is progressively transforming the feasibility and scalability of prefabricated deep renovation processes [50]. Technologies such as Building Information Modeling (BIM), laser scanning, photogrammetry, Digital Twins, parametric modeling, and AI-assisted optimization enable the acquisition of highly accurate as-built geometries and facilitate the mass customization of prefabricated components [51,52].

This capability is particularly important for renovation projects because each existing building presents unique geometric, structural, and operational conditions. Through scan-to-BIM methodologies, existing buildings can be digitally reconstructed with millimetric precision, enabling the design and fabrication of tailored prefabricated modules compatible with the actual building geometry [45]. BIM environments further support multi-disciplinary coordination between architectural, structural, and MEP systems while enabling advanced simulation workflows for energy performance, carbon emissions, and installation planning [53–55]. Recent advances in building energy simulation and optimization methods are further accelerating the integration between industrialized renovation processes and predictive performance assessment tools [54–57]. Within this digital ecosystem, computational estimators integrated with BIM are increasingly utilized to evaluate

whole-life performance and predict the salvage potential of structural components at the building's end-of-life stage [58].

More recently, Digital Twin technologies have introduced the possibility of integrating real-time operational data into renovation workflows, enabling predictive maintenance, continuous performance monitoring, and adaptive building management strategies [51,52]. At the same time, advances in automation, robotic manufacturing, and industrial robotics are progressively reducing production costs while improving the precision and scalability of off-site manufacturing processes [18]. DIGITALEUROPE [49] further emphasizes how digital building transformation strategies will become central for enabling Europe's future green renovation ecosystem.

Nevertheless, despite these technological advances, the European renovation ecosystem still faces a critical implementation gap between technological potential and real market deployment. Many Horizon-funded projects have demonstrated technically promising integrated retrofit concepts, yet only a limited number of these solutions have evolved into commercially mature and widely deployable products [20].

3. Materials and Methods

To guarantee methodological transparency, reproducibility, and a rigorous scientific approach, the research design is operationalized through a structured, three-tier workflow. This operational protocol ensures that the data processing sequence remains completely auditable, guiding the systematic transition from unstructured multi-source technical documents to a harmonized relational database environment. The systematic progression of the research framework—encompassing data identification, screening, and subsequent data extraction and classification—is delineated in the methodological flowchart below (Figure 2).

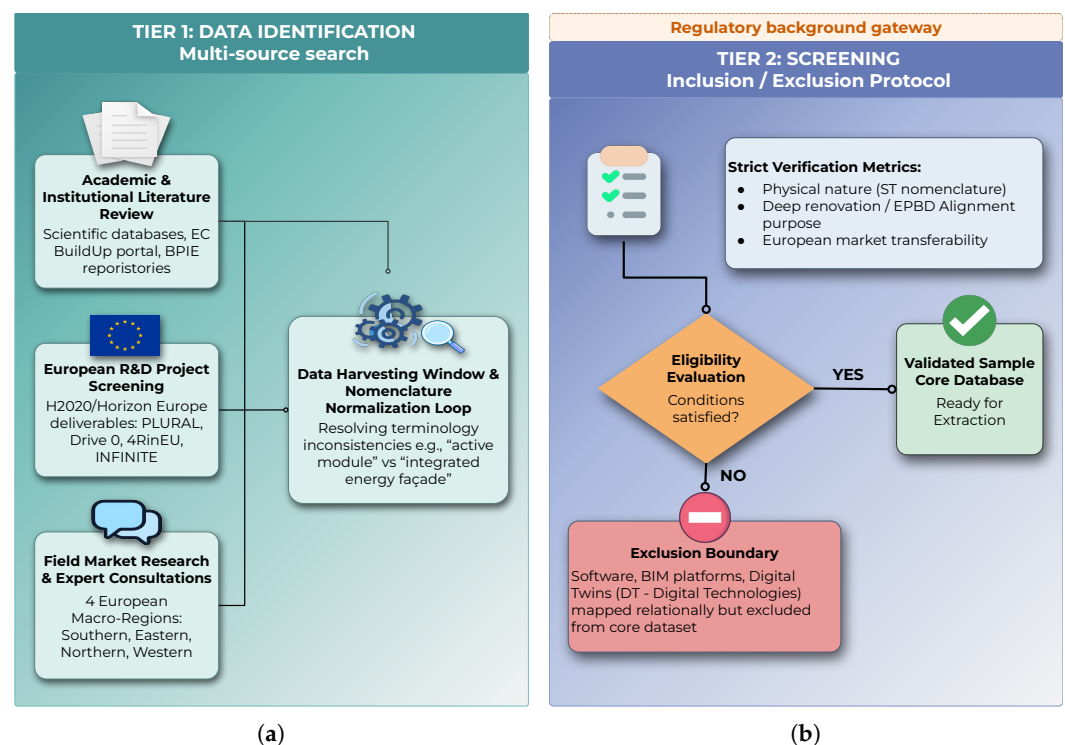


Figure 2. Cont.

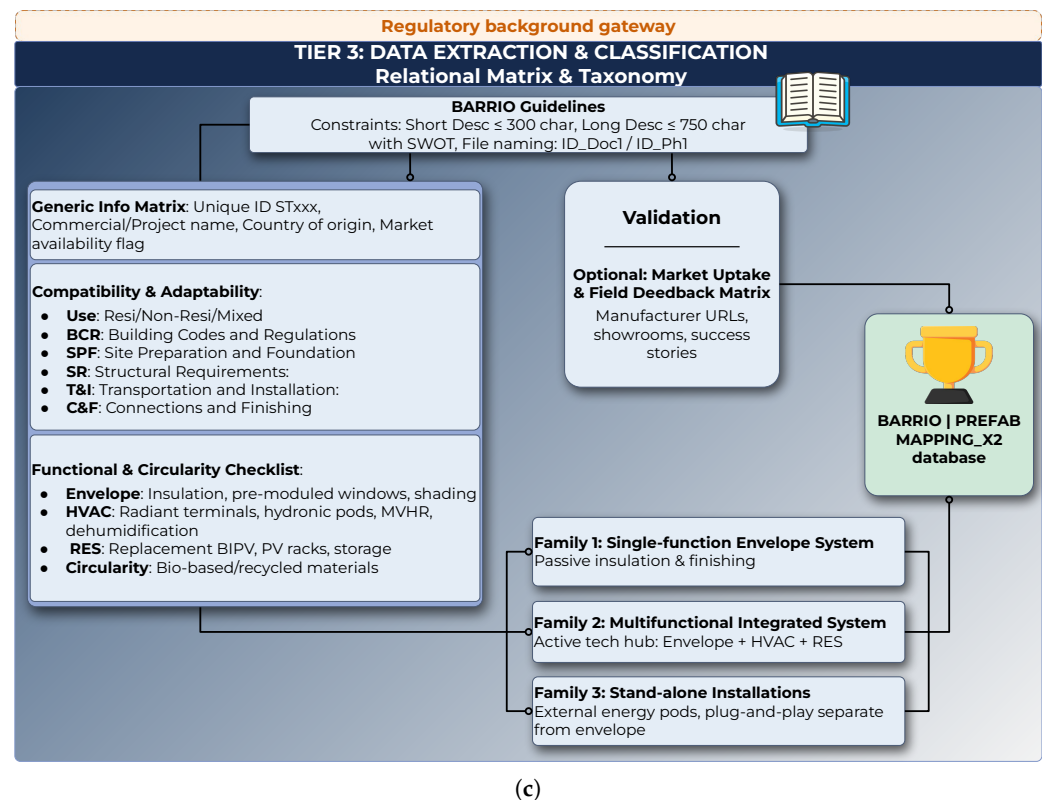


Figure 2. Methodological flowchart: (a) data identification, (b) screening (inclusion/exclusion), and (c) data extraction and classification.

3.1. Data Collection Protocol and Sample Definition

The foundational repository for this study consists of the collaborative relational dataset compiled within the framework of the European LIFE project BARRIO (LIFE23-CET-BARRIO), specifically designated as the “BARRIO | PREFAB MAPPING_X2” database. Conceived as a structured mapping environment, this database consolidates fragmented technological information originating from academic research, industrial innovation, and European demonstration projects into a harmonized, multi-scalar, and reproducible dataset. To overcome the chronic fragmentation typical of the European energy renovation sector and to establish a representative market overview, a comprehensive data harvesting campaign was executed over a defined temporal window. The data collection architecture integrated three complementary primary and secondary research tracks, structured to minimize inconsistencies and maximize geographical cross-fertilization, as systematized in Table 3.

Table 3. Systematic breakdown of the multi-source data collection strategy and regional mapping tracks.

Research Stream	Target Repositories and Channels	Primary Data Extracted
(a) Academic & Institutional Review	Indexed scientific databases, EC BuildUp portal, and Buildings Performance Institute Europe (BPIE) repositories.	Historical mapping frameworks, cross-border classification logics, and technology readiness level (TRL) benchmarks.
(b) European R&D Project Screening	Public deliverables, technical reports, and pilot building documentation from H2020 and Horizon Europe consortia (e.g., PLURAL, Drive 0, ENSNARE, 4RinEU, INFINITE).	Performance metrics, technical geometries, and normalization of heterogeneous product nomenclatures.
(c) Market Investigations & Surveys	Targeted field surveys and iterative structured interviews conducted by LIFE BARRIO partners across four European macro-regions.	Commercial supply chain capacity, verification of active market availability, and regional climatic or regulatory variations.

This multi-source harvesting campaign was operationalized through a structured three-step screening protocol to ensure transparency, objectivity, and reproducibility:

1. **Phase 1: Initial Technology Harvesting.** The international partners of the BARRIO consortium conducted a comprehensive cross-border search using designated channels: indexed scientific databases for the academic literature, CORDIS and BuildUp portals for EU-funded projects (H2020 and Horizon Europe), and regional market surveys within the partner countries (Italy, Spain, Slovenia, and Bulgaria). This initial raw harvesting yielded a repository of 68 distinct physical prefabricated technologies (ST—technological prefabricated solutions).
2. **Phase 2: Semantic Deduplication and Nomenclature Normalization.** Because different research consortia and industrial manufacturers frequently adopt highly heterogeneous terminologies for identical technological concepts, a rigorous deduplication process was enforced. Entries were grouped based on their core cross-sectional layout and functional subsystems. Duplicates arising from overlapping project acronyms or alternative brand nomenclatures (e.g., classifying identical configurations labeled as “active envelope modules”, “integrated energy façades”, or “multifunctional panels” under a single generic technical solution) were systematically merged, ensuring that each of the 68 entries represented a unique technological configuration.
3. **Phase 3: Eligibility and Market Readiness Screening.** The consolidated repository of 68 entries was then subjected to the strict inclusion and exclusion boundaries detailed in Table 4. To eliminate subjectivity, the final bifurcation of the sample was governed by two objective, verifiable criteria detailed in Section 4.1: entries were classified as “Commercially Available” ($N = 26$) only if they possessed a verified Technology Readiness Level (TRL) of 9 combined with an active, publicly accessible product catalogue or website. The remaining entries ($N = 42$) that failed to meet these criteria were classified as pre-commercial research prototypes and archived in Appendix A to map the medium-to-long-term R&D trajectory of the sector.

Table 4. Inclusion and exclusion protocol for database eligibility and technological sample boundaries.

Dimension	Inclusion Criteria (Eligible)	Exclusion Boundaries (Ineligible)
Physical Materiality	Physical, pre-assembled off-site components or industrialized kits classified under the ST—solutions and technologies nomenclature.	Purely conceptual proposals, fragmented construction details, or conventional on-site raw materials and wet assembly systems.
Functional Purpose	Explicitly engineered, piloted, or commercially marketed for the deep renovation and decarbonization of the existing building stock (EPBD alignment).	Technologies exclusively optimized for new construction applications that lack adaptability to irregular, occupied building retrofits.
Geographical Scope	Technologies developed, piloted, or actively commercialized within the European Union market periphery.	Technologies restricted to non-European regulatory, climatic, or market conditions.
Digital Interoperability	Relational tracking within the overarching BARRIO framework to preserve multi-system interaction.	Software applications, BIM engines, Digital Twin platforms, and algorithmic optimization toolkits (DT—digital technologies).

The explicit exclusion of digital technologies (DT) from this specific manuscript’s core dataset ensures that the descriptive analysis remains strictly focused on the physical hardware, structural constraints, and active equipment components of industrialized retrofits. To enforce semantic discipline across the international consortium, the repository

architecture incorporates strict data engineering rules governed by the “Guidelines” framework. Technical entries are assigned an alphanumeric unique ID using a prefix convention: MGxxx for theoretical methodologies, STxxx for physical solutions, and DTxxx for digital systems. Furthermore, a strict file-naming protocol links external verification sources to the matrix, renaming engineering documents as ID_Doc1 (stored in the 01-Document directory) and image assets as ID_Ph1 (stored in the 02-Photo directory). To ensure full transparency, reproducibility, and to allow future updates by the scientific community, the complete dataset of the mapped physical solutions is provided in Appendix A.

3.2. Database Structure and Variables Extraction

Following sample definition and validation, a standardized data extraction grid was implemented to convert heterogeneous technical documentation into a structured, multi-layer relational matrix. To mitigate the risk of data entry fragmentation, the extraction grid relies on a precise syntactic architecture where qualitative text descriptions are bound by strict formatting thresholds. The short description field is constrained to a maximum of 300 characters, forcing technical synthesis, while the long description field is limited to 750 characters and must explicitly incorporate a simplified SWOT matrix covering strengths, weaknesses, and barriers. This strict capping prevents user interface corruption during data migration to web-based dashboards and eliminates the risk of “data orphans” during cross-border transferability analyses.

To enable advanced logical queries across the catalog, the technical fields extracted from the documentation are mapped into a standardized binary matrix capturing the presence or absence of each technical attribute. For each validated solution, these parameters were organized into three distinct, interdependent informational blocks, as summarized in Table 5.

Table 5. Systematic overview of extracted database variables and strategic analytical purposes.

Informational Block	Extracted Variables & Parameters	Analytical & Strategic Purpose
General Information	Unique alphanumeric ID, commercial or project-derived name, country of origin, and market availability flag (Yes/No).	Establishes the core cataloging structure, maps geographical distribution, and benchmarks market readiness levels (TRL).
Compatibility & Adaptability Constraints	Building-use destination, ownership targets, geometric limitations, structural requirements, and physical process destination.	Acts as a proactive risk-management matrix; maps physical boundaries, constructability, and regulatory thresholds restricting large-scale deployment.
Functional & Circularity Breakdown	Passive envelope features, integrated HVAC layers, renewable energy sources (RES), and circularity indicators.	Decomposes multi-system kits; evaluates the level of technological multi-functionality and circular economy alignment.

Regarding the first block, geographical data are concurrently normalized by binding each entry to standardized European geo-clusters (e.g., “Mediterranean Area—Italy and Spain”) rather than relying on generic, unformatted inputs, thereby ensuring comparative consistency across the sample. Within this framing, the percentage distributions presented in the geographic charts (Figures 3 and 4) explicitly indicate the relative proportion of prefabricated solutions that are validated and technically applicable for physical deployment within those specific territorial boundaries. The concurrent inclusion of individual nation-states (such as Italy, Spain, or France) alongside broader macro-regions (such as Eastern Europe) does not represent an analytical overlap or double-counting error. In-

stead, this multi-scalar classification accounts for industrialized solutions whose technical configurations and regulatory compliance paths have been explicitly engineered and validated to target either localized domestic markets or overarching regional climatic zones simultaneously. The second block acts as a proactive risk-management module, tracking the physical boundaries, regulatory thresholds, and constructability limits that restrict large-scale urban deployment. To prevent structural and operational field failures during installation, the database tracks both standardized internal risk codes and physical adaptation layers designed to absorb the irregularities of legacy substrates. This compatibility layer specifically evaluates the integration of punctiform anchoring systems—such as specialized adjustable telescoping brackets or rotating ball joints designed to absorb significant wall out-of-plumb deviations in historical and post-war building façades—and analyzes the capacity of anchoring sub-frames to withstand localized wind-shear profiles in mid- and high-rise structures. Concurrently, the standardized risk codes within this block are categorized into five primary operational dimensions, supplemented by critical transversal performance safeguards:

- **SPF | Site Preparation and Foundation:** Tracks critical pre-installation parameters, including geotechnical survey performance to evaluate soil bearing capacity and sub-surface stability (SPF1), precise ground grading and leveling requirements to establish a stable structural base (SPF2), foundation typology matching (e.g., concrete slab-on-grade, pier and beam, or basement configurations) (SPF3), and the pre-existence of accessible utility connections for on-site execution (SPF4).
- **BCR | Building Codes and Regulations:** Enforces absolute compliance with mandatory localized regulations, highlighting urban planning and legal boundaries. This encompasses generic local building codes determining structural and energy performance standards (BCR1), the mandatory administrative workflow for obtaining construction permits (BCR2), and strict verification of zoning regulations to ensure land-use alignment and mitigate property conflicts (BCR3).
- **SR | Structural Requirements:** Defines mechanical resistance limits and environmental stress boundaries. This includes the load-bearing capacity of the host foundation and supporting frames against component dead weights, snow, and occupancy live loads (SR1), geographic wind resistance thresholds and shear profile mitigation (SR2), and mandatory seismic design criteria required in high-activity installation zones (SR3).
- **T&I | Transportation and Installation:** Assesses the logistical boundaries of the assembly loop, tracking physical site access limitations for heavy logistics and delivery vehicles (T&I 1), the required deployment parameters for lifting machinery or crane equipment (T&I 2), and the critical availability of certified, highly skilled labor necessary to guarantee quality and safety protocols during assembly (T&I 3).
- **C&F | Connections and Finishing:** Governs the final integration and handover stages. This tracks standard utility on-site network connections (C&F1), proper insulation and weatherproofing sealing techniques implemented to secure the building envelope against thermal bridging and atmospheric elements (C&F2), and the completion of custom interior and exterior architectural finishes (C&F3).
- **Accessibility:** If the prefabricated solution is intended for use by people with disabilities, ensure that the design and construction comply with all accessibility requirements and standards.

- **Fire Safety:** The structure must meet all applicable fire safety standards, including the use of fire-resistant materials and the incorporation of adequate fire protection systems, such as smoke detectors and sprinklers.
- **Sustainability:** Consider using sustainable materials and construction practices to minimize the environmental impact of the prefabricated solution. This may include using recycled or renewable materials and implementing energy-efficient design features.

Finally, the third block (Functional & Circularity Breakdown) is engineered as a structural checklist organized on a hierarchically nested four-level tree layout (R1–R4) to systematically map multi-system integration. Level 3 (R3) establishes the technical macro-categories—Envelope, HVAC, and RES—which dictate the row indicators at Level 4 (R4). Within the envelope domain, the grid tracks factory-integrated wall or roof insulation cores (mineral wool, EPS, or bio-based matrices), factory-sealed fenestration with high-performance airtight membranes, motor-driven integrated shading devices, and special add-on architectures like self-supporting prefabricated balcony modules designed to eliminate complex structural slab thermal bridges.

Within the HVAC domain, the analysis maps the embedment of terminal heating or cooling units (e.g., hydronic radiant capillary tubes or electric circuits), containerized domestic hot water (DHW) plant pods, and decentralized mechanical ventilation units with heat recovery (MVHR) channels—the most critical active pattern discovered for occupied multi-family complexes. Dehumidification layers are concurrently tracked to assess summer comfort within the Mediterranean geo-cluster. The renewable energy section investigates building-integrated photovoltaics (BIPV) where active solar glazing or active cladding skins structurally substitute standard exterior finish materials, alongside conventional PV or solar thermal racks, integrated battery skids, and micro-wind turbine integrations. Circularity indicators track secondary material content, the percentage of bio-based fibers, and the use of dry mechanical connections, exposing the current lack of harmonized circularity assessment protocols within the European prefabrication sector.

3.3. The Taxonomy Framework

To resolve terminology inconsistencies and bypass commercial branding variances, the validated physical solutions were organized using a standardized three-category taxonomy. Rather than seeking to introduce an entirely new theoretical classification—as the technical distinctions between passive envelopes, active multi-functional building skins, and decentralized plug-and-play installations are already well documented in the building physics literature and institutional reports [20,22,41]—this taxonomy is adopted as a pragmatic sorting framework. Clustered according to their level of multi-system integration and structural interface, the technologies are divided into three mutually exclusive families detailed in Table 6.

The adoption of this standard taxonomy provides a consistent operational baseline required to systematically map heterogeneous physical configurations. Instead of serving as an isolated conceptual advance, this classification acts as a structural prerequisite for the applicability and risk-mapping analysis: it allows for the clear cross-referencing of distinct technology families against their specific technical applicability constraints, regulatory boundaries (BCR), and structural risk codes (SR), while establishing a rigorous architectural foundation for the subsequent quantitative Prefabrication Readiness Index (PRI).

Table 6. Taxonomic classification framework for prefabricated physical solutions based on system integration levels.

Taxonomic Family	Core Functional Configuration & Embedded Subsystems	Observed Market Maturity State
Single-Function Envelope Systems (Façade/Roof)	Purely passive off-site modular loops providing thermal insulation, airtightness, moisture regulation, and architectural finishing without active components.	High market readiness; consolidated industrial scalability across European regions.
Multi-functional Integrated Systems (Façade/Roof)	Hybrid active building skins integrating passive insulation with embedded HVAC layers, micro-integrated MVHR ducting, radiant hydronic components, or BIPV finishes.	Emerging innovation frontier; predominantly confined to Horizon pilot projects.
Stand-Alone Installations	Prefabricated technical units physically separate from the primary envelope, enclosed in external housings or pods (e.g., energy pods, rooftop units, thermal skids).	Moderately mature; engineered to minimize on-site commissioning and occupant disruption.

3.4. Methodological Limitations and Study Boundaries

While the developed framework establishes a rigorous, operational database for selected prefabricated components, several inherent methodological boundaries and scoping characteristics should be explicitly outlined to contextualize the findings and guide future research tracks:

- **Geographical Distribution and Consortium Footprint:** A primary boundary of this technology supply mapping concerns the regional distribution of the harvested sample. Due to the operational framework of the LIFE23-CET-BARRIO project, the dataset exhibits a concentration of solutions originating from the Mediterranean area (specifically Italy and Spain). Consequently, historically established prefabrication markets—such as the Netherlands (driven by the Energiesprong framework), Germany, and Scandinavian countries—are less represented in the commercialized sample. For this reason, the observed dataset shares and technological distribution profiles represent an exploratory supply-side overview of selected cases and should be contextualized rather than generalized as an absolute assessment of the entire European building stock.
- **Exploratory and Descriptive Nature of the Analysis:** The analysis delivered in this study relies on descriptive frequency counts and percentage breakdowns within the harvested repository. Given the size of the commercialized sample ($N = 26$), the application of advanced inferential statistics or predictive causal modeling was deliberately avoided to preserve statistical validity and prevent over-interpretation. This study functions as an exploratory overview of physical hardware availability rather than a macroeconomic market assessment. Consequently, rather than executing formal quantitative correlation testing, the structural polarization and regional technology distributions are examined and explained qualitatively against contextual policy frameworks and industrial structural determinants within the Discussion section.
- **Qualitative Data Extraction and Reliability:** The population of the database fields and the subsequent extraction of categorical parameters were based on qualitative technical documentation, such as commercial brochures, and official project deliverables. To minimize input errors, the data entry and verification process was performed collaboratively by the entire project partnership, allowing for collective cross-checking of the information. However, because formal statistical inter-rater reliability testing

was not conducted, this manual classification process inherently carries a degree of subjective interpretation and potential coding bias.

- **Preliminary Nature of Circularity Indicators:** The evaluation of the circular economy dimension within this framework is based on a preliminary verification of declared recycled or reused material content as stated in the available technical literature. While this approach successfully captures the technical claims found in product brochures, it does not substitute for detailed Life-Cycle Assessments (LCA), whole-life carbon calculations, or formalized quantification of Design for Disassembly (DfD) efficiency rates, which remain key objectives for subsequent research phases.
- **Focus on Supply-Side Hardware vs. Socio-Economic Dynamics:** This research intentionally focuses on the physical and technical installability side of industrialized retrofits. Accordingly, macroeconomic market indicators—such as unit costs, deployment volumes, and commercial sales-based market shares—fall outside the designated perimeters of this work. To avoid terminological confusion, percentages presented in the descriptive charts represent the **dataset share** (i.e., the relative proportion of mapped physical technological configurations in our repository) rather than commercial sales volumes.
- **Analytical Separation from Enabling Digital Workflows:** To maintain a precise focus on structural and equipment hardware components, software applications, BIM engines, and Digital Twin enablers were excluded from the core quantitative hardware dataset. This defined scope establishes an analytical boundary between the physical prefabrication hardware and its digital enabling pipelines (such as Scan-to-BIM or DfMA modeling), which represent separate domains of investigation.
- **Circularity Disclosures vs. Life-Cycle Quantification:** The evaluation of the circular economy dimension within this framework tracks the explicit technical and promotional disclosures found in the available commercial literature, rather than measuring physical material loops. While this approach successfully evaluates market readiness in terms of certified commercial supply claims, it is bounded by a binary parameters matrix. Consequently, it functions as an assessment of circularity documentation capacity and design disclosure trends; it does not substitute for quantitative Life-Cycle Assessments (LCA), embodied carbon calculations, or formalized deconstruction recovery rates. However, the finding that circularity features show limited explicit integration is strictly justified under this scope, as it reflects a verified scarcity of formalized circular certifications and explicit architectural disclosures provided by manufacturers to practitioners. Crucially, this observed lack of quantitative circularity depth is not a methodological oversight of this study but an empirical finding in itself, exposing a severe reporting gap within the current prefabrication supply chain.

4. Results

To bridge the gap between building theory and industrial practice, this section delivers an operational overview of commercially available prefabricated solutions for energy renovation. Evaluated within the framework of the BARRIO project, the dataset shifts the analytical focus from theoretical thermal modeling to empirical technical readiness and availability, exposing the systemic bottlenecks, geographical characteristics, and material perimeters governing the investigated options. In strict alignment with this study's configuration as a technology supply mapping rather than an exhaustive macroeconomic market assessment, the frequencies, dataset shares, and categorical breakdowns delivered in this section are descriptive and exploratory in nature. For a comprehensive overview of the geographical distribution profiles, qualitative data extraction variables, and socio-economic

boundaries that define the perimeters of this supply mapping, the reader is explicitly referred to Section 3.4 (Methodological Limitations and Study Boundaries).

4.1. Overview of the Mapped Solutions

The systematic mapping campaign initially harvested a total repository of 68 physical prefabricated entries to capture the full spectrum of regional developments. However, to fulfill the primary objective of this study—providing a pragmatic, real-world assessment of immediate industrial capacity—the descriptive analysis presented from this point forward isolates and focuses exclusively on the filtered subset of 26 commercially available, market-ready solutions. In this framework, a solution was objectively classified as commercially available if it strictly satisfied two simultaneous operational criteria: (i) it had achieved a Technology Readiness Level (TRL) equal to 9, and (ii) it possessed an active, publicly accessible manufacturer website or product catalogue. Conversely, entries that failed to meet both criteria were categorized as pre-commercial research prototypes.

To maintain analytical clarity while preserving the comprehensive scope of the mapping campaign, the remaining 42 pre-commercial research prototypes, laboratory concepts, and pilot-scale experiments are systematically compiled and cataloged in Appendix A. This organizational distinction ensures that the subsequent technical breakdowns, functional evaluations, and risk matrices focus strictly on off-the-shelf industrial solutions immediately available to building sector professionals and construction practitioners, while the appendix serves to outline the broader mid-to-long-term R&D trajectories of the sector.

Concurrently, it must be acknowledged that isolating the commercialized subset introduces a conservative operational bias, potentially understating the overall technological dynamism of the European prefabrication ecosystem. However, this screening is methodologically necessary to provide a realistic assessment of immediate supply-chain capacity, preventing laboratory-stage configurations from artificially inflating the perceived market readiness of active, multi-system components.

4.2. Geographical Distribution and Dataset Share of the Commercialized Cohort

To prevent any terminological ambiguity, all percentages presented in this section and throughout the manuscript refer to the dataset share (i.e., the relative proportion of distinct technological configurations mapped within our research database) rather than commercial sales-based market shares. Since this study is configured as a technology supply mapping, these metrics represent cataloged technological diversity and availability rather than commercial sales volumes.

When transitioning the empirical data from traditional separate tracking to an integrated format, the operational discrepancy between mature passive insulation systems and active multi-system architectures becomes highly visible.

Key Finding: *The results show a clear polarization: while basic passive systems are widely commercialized and ready for immediate field deployment, highly integrated multi-functional systems are still largely confined to the prototyping (pre-commercial) phase within European pilot projects.*

This polarization exposes a critical technological supply gap. Single-function envelope systems (Façade & Roof)—which provide exclusively thermal insulation, basic weather-proofing, and superficial architectural cladding—have achieved full commercial availability and technological maturity. Conversely, multi-functional integrated systems (Façade & Roof) struggle to cross the commercialization chasm, remaining highly dependent on European R&D funding streams (e.g., Horizon Europe consortia) due to high upfront capital investments and fragmented industrial supply chains. Stand-alone installations (energy

pods/skids) reflect a similar trend of R&D confinement, with zero immediate commercial offerings currently available within the audited repository.

To eliminate any potential confusion or perceived mathematical discrepancies between different data displays, the technological volumes, commercial maturity layers, and institutional drivers are integrated into a single unified matrix in Table 7. This comprehensive categorization maps the exact absolute frequencies (N) extracted from the database alongside their relative percentages (%) calculated strictly within each distinct taxonomic macro-family, establishing a direct, self-explanatory mathematical synchronization.

Table 7. Unified matrix of technological readiness, dataset volumes, and primary regulatory drivers across taxonomic families (data source: BARRIO database, compiled as of March 2025).

Taxonomic Family	Commercialized		Research Prototype		Primary Regulatory Driver/Funding Source
	N	%	N	%	
Single-Function Envelope Systems (Façade & Roof)	19	65.5%	10	34.5%	EPBD Mandates, National Energy Codes (e.g., Italy Superbonus, Spain PIREP)
Multi-Functional Integrated Systems (Façade & Roof)	7	20.6%	27	79.4%	Horizon Europe, H2020 Research Grants; CORDIS and BuildUp project deliverables
Stand-Alone Installations	0	0.0%	5	100.0%	Industrial R&D, Decentralized HVAC Policies

To map these solutions geographically, Figures 3 and 4 illustrate the primary territorial scale of certified technical validation for the market-ready cohorts. This metric identifies the specific administrative or geo-climatic jurisdiction where the system has completed formal regulatory testing, compliance pathways, or local pilot validation. To ensure mathematical consistency and avoid double-counting within the percentage distributions, the classification uses a strict multi-scalar hierarchy where each technology is assigned to its broadest validated scale of certification:

- **National Scale:** Technologies engineered and validated strictly for a specific country (often accelerated by localized public incentives like Italy’s Superbonus 110% or Spain’s PIREP program) are mapped under their respective nation-states (e.g., Italy, Spain, France).
- **Macro-Regional Scale (Geo-Clusters):** Technologies possessing transnational compliance (such as CE marking or European Technical Assessments) or validated through multi-partner European pilot frameworks are mapped exclusively under macro-regional clusters (e.g., Eastern Europe, North-East Europe) or International frameworks. Under this rule, a solution certified for the “Eastern Europe” geo-cluster is not duplicated within localized nation-states (like Bulgaria or Estonia), ensuring that all categories in the charts remain mutually exclusive.

A crucial methodological clarification is required regarding the calculation baseline used for the percentages in the geographical charts. Because industrial prefabrication tends to treat the building envelope as a continuous, integrated system, several solutions are designed as “hybrid kits” capable of addressing both vertical walls (façades) and sloped/flat roofs, including transitional interface nodes (such as eaves or parapets). Furthermore, because a single technological system can be certified or validated across multiple geographic scales or national jurisdictions simultaneously to target different regional markets, the total number of technical validation records (N_{val}) can exceed the absolute number of distinct physical systems (N). Specifically, the single-function commercialized cohort ($N = 19$) yields a total of $N_{\text{val}} = 34$ distinct geographic validation records, while the multi-functional

commercialized cohort ($N = 7$) maps to exactly $N_{\text{val}} = 7$ validation records (one primary certified scale per system).

When isolating the deployment validation profiles across the market-ready single-function envelope systems family (Figure 3, where percentages are calculated over the total certified validation records, $N_{\text{val}} = 34$), the distribution confirms a clear priority axis centered on localized national certifications, led by Spain (23.53%) and Italy (20.59%), followed by France (14.71%). The remaining technical validation profile is shared among regional contexts such as Germany, Romania, and the North-East Europe cluster (5.88% each), while a steady baseline allocation of 2.94% each is registered across localized nation-states (Ireland, Czech Republic, The Netherlands, Bulgaria, Austria, Estonia) and trans-national boundaries (Eastern Europe, International frameworks).

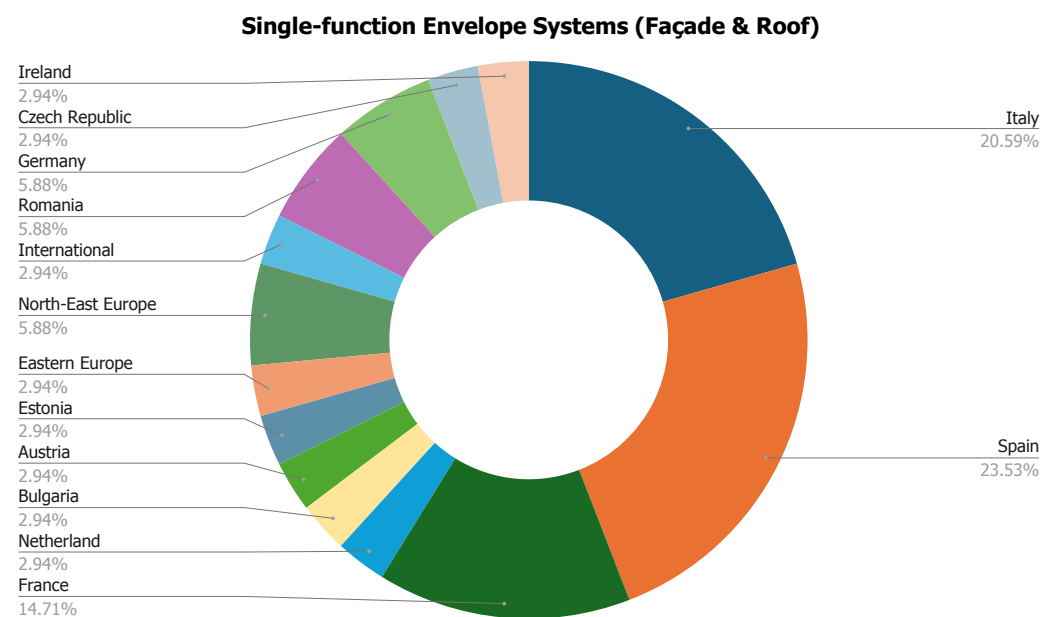


Figure 3. Geographical distribution of primary certified technical validation scales for market-ready single-function envelope systems (Façade & Roof). (Percentages calculated over total geographic validation records, $N_{\text{val}} = 34$, representing $N = 19$ distinct commercialized systems. Data source: BARRIO database, compiled as of March 2025).

When shifting the analysis to the market-ready multi-functional integrated systems family (Figure 4, where percentages are calculated over the total validated scales, $N_{\text{val}} = 7$, perfectly matching the $N = 7$ commercialized active solutions), the geographical distribution of certified technical validation exhibits a highly concentrated, nation-specific profile. Within this active, multi-system cohort, Italy establishes a dominant baseline, capturing a 42.86% share of the validated repository entries. Conversely, the remaining territorial validation is distributed in perfectly balanced quadrants across Spain, the United Kingdom, the Czech Republic, and France, with each nation registering a secondary baseline allocation of 14.29%. This specific breakdown demonstrates that while multi-functional active skins face steeper regulatory, interface, and financial hurdles across the European Union, targeted multi-partner collaboration tracks and highly advanced regional industrial clusters have successfully driven a select core of multi-technological solutions toward certified commercial readiness.

Finally, a critical structural finding of this supply mapping concerns the total absence of market-ready, commercially available stand-alone installations within the audited sample. While the broader repository tracks 5 experimental research prototypes confined to pilot-

scale applications (as compiled in Table 7 and detailed in Appendix A), zero solutions have successfully completed the research-to-market transition.

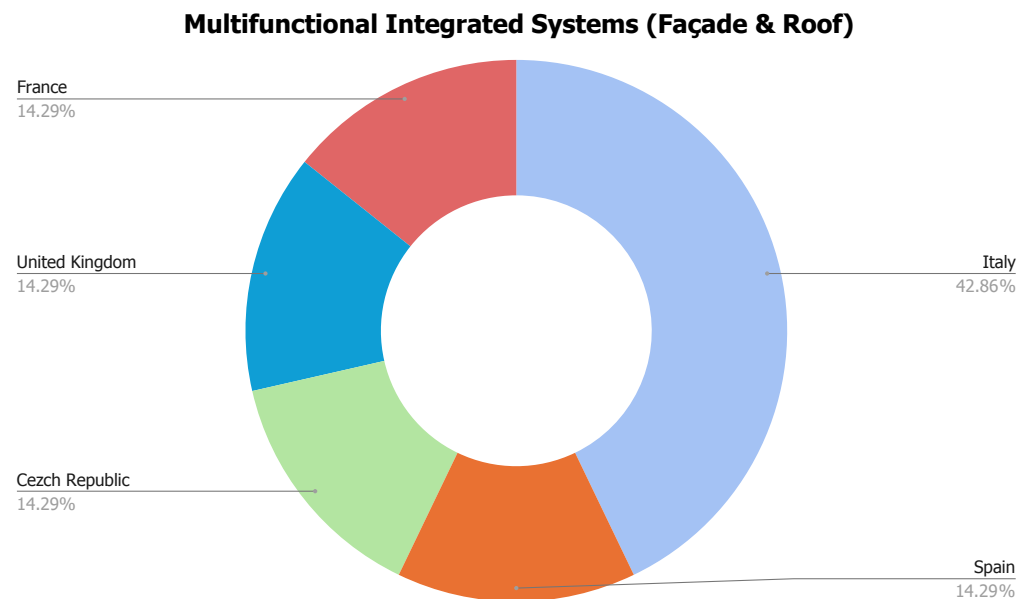


Figure 4. Geographical distribution of primary certified technical validation scales for market-ready multi-functional integrated systems (Façade & Roof). (Percentages calculated over total validation records, $N_{\text{val}} = 7$, representing $N = 7$ distinct commercialized active systems. Data source: BARRIO database, compiled as of March 2025).

This commercial vacancy is directly dictated by severe physical, logistical, and spatial bottlenecks characteristic of the Southern European built environment. First, historic and post-war urban centers in Italy and Spain feature high-density property alignments, narrow public right-of-ways, and constrained interior courtyards that mechanically prevent the ground-level placement or crane-assisted hoisting of heavy, rigid external central utility pods. Second, routing the extensive vertical distribution networks (such as hydronic piping or centralized mechanical ventilation ducts) from an external stand-alone pod into multiple individual occupied apartments requires highly invasive structural penetrations through existing interior spaces, completely neutralizing the core non-intrusive value proposition of off-site prefabrication. Finally, from a market perspective, manufacturers face a severe socio-organizational deadlock: deploying a shared external technical installation requires a complex multi-owner condominium voting consensus and facility management restructuring to manage collective energy billing and maintenance. Without aggregated public procurement tracks or explicit legal frameworks governing shared off-site technical assets, the investment required to certify and commercialize stand-alone pods remains economically unviable for industrial producers, leaving this sector strictly confined to experimental, publicly subsidized R&D clusters.

4.3. Functional Breakdown (Envelope, HVAC, RES) of the Commercialized Cohort

Deconstructing the physical hardware configurations of the 26 commercially available solutions through the database's nested hierarchy allows for a detailed analysis of what is technically embedded inside the market-ready modules.

4.3.1. Envelope Functionalities

It must be explicitly noted that the architectural parameters are tracked within combined categories encompassing both façade and roof assemblies to systematically address transition interfaces (such as eave junctions, parapets, or thermal bridge perimeter nodes).

Consequently, the quantitative breakdown registers roof-specific functionalities side-by-side with wall elements within the same taxonomic families, reflecting the multi-element versatility of modular construction kits.

As illustrated in Figure 5, within the Single-Function Envelope Systems (Façade & Roof) macro-category, 11 solutions integrate factory-fitted wall insulation, 7 feature dedicated roof components, and 7 incorporate other basic finishes, while 2 include window kits and 2 integrate shading devices. Shifting the focus to Multi-Functional Integrated Systems (Façade & Roof) cohort, the functional density reflects a more targeted system pairing: 6 solutions incorporate factory-fitted wall insulation, 5 feature integrated windows, 2 include integrated shading devices, and 1 incorporates a dedicated roof subsystem, while zero entries are mapped under the other category.

Functionalities - Envelope

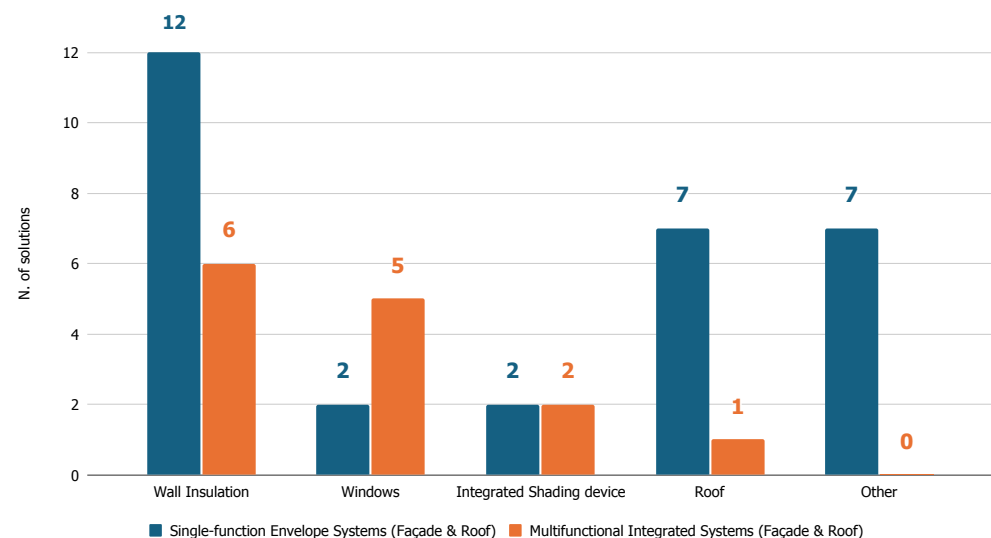


Figure 5. Comprehensive breakdown of embedded envelope functionalities across single-function and multi-functional modules (data source: BARRIO database, compiled as of March 2025).

4.3.2. HVAC Integration

When analyzing active building service layers, the commercialized dataset exposes the deep technical fragmentation of mechanical systems within industrialized prefabrication. Within the market-ready sample of multi-functional solutions featuring HVAC elements, decentralized mechanical ventilation units represent the dominant integration pattern.

As charted in Figure 6, within the single active Multi-Functional Integrated Systems (Façade & Roof) cohort, ventilation appears in 5 solutions, confirming it as the preferred configuration because integrating air distribution is technically straightforward—requiring primarily the routing of passive ducts and structural penetrations within the panel core. In sharp contrast, embedding true thermal production machinery directly into the commercial modules remains a rarity, with heating and cooling layers limited to 2 solutions each, and domestic hot water (DHW) components restricted to a single entry. Crucially, despite this study’s focus on Southern European cases where summer latent loads are high, specialized dehumidification features register no entries, matched by the absence of solutions categorized under other active subsystems. Condensate management, acoustic vibrations, structural weight, and maintenance access barriers continue to prevent manufacturers from scaling these advanced active thermomechanical solutions commercially.

Functionalities - HVAC

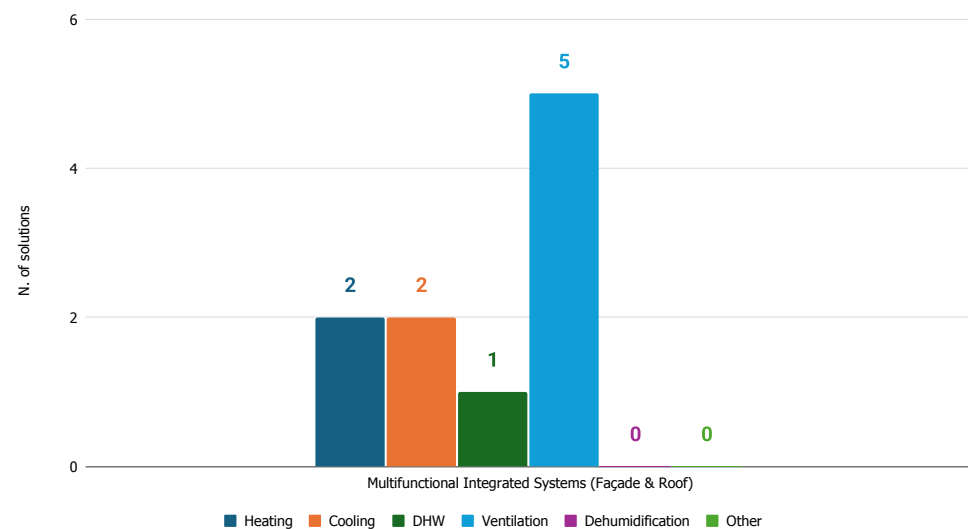


Figure 6. Distribution of embedded HVAC functionalities within active multi-functional prefabricated façade solutions (data source: BARRIO database, compiled as of March 2025).

4.3.3. Renewable Energy Sources (RESs)

The integration of local generation technologies within commercial systems is heavily dominated by solar architectures. While Building-Integrated Photovoltaics (BIPV) and conventional PV rack attachments are registered, they operate in a technological silo. As systematically visualized in Figure 7, within the active Multi-Functional Integrated Systems (Façade & Roof) cohort, BIPV and standard photovoltaic layouts account for 3 entries each. Conversely, the commercial dataset highlights a critical integration gap regarding storage and alternative thermal harvesting, registering only a single entry for integrated battery storage components, while solar thermal collector networks, wind power options, and alternative subsystems (categorized as other) all register no entries. This configuration demonstrates that local generation and structural storage remain industrially disconnected within the available offerings, treating the commercial building envelope primarily as a structural support rather than a fully optimized, self-contained energy node.

Functionalities - RES

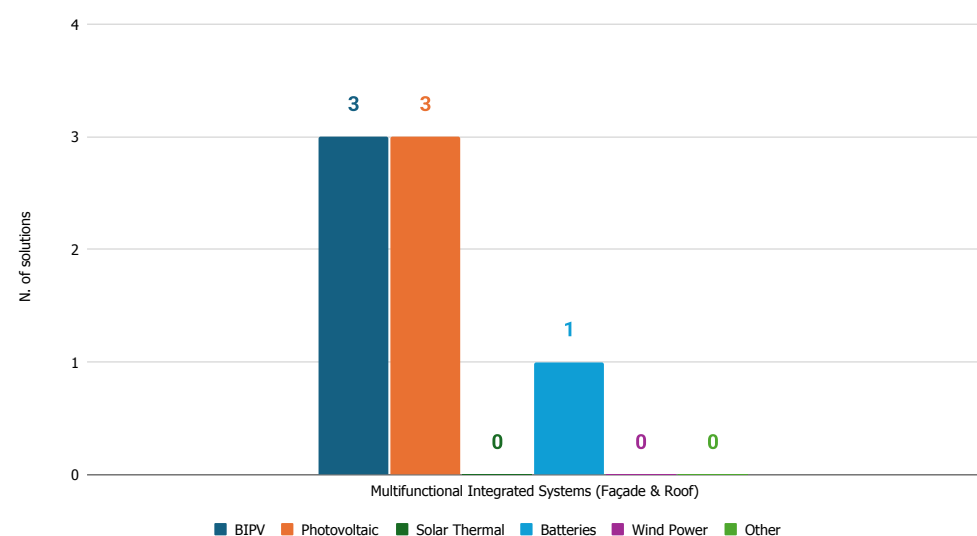


Figure 7. Analysis of renewable energy source (RES) integration patterns within multi-functional façade systems (data source: BARRIO database, compiled as of March 2025).

4.4. Technical Applicability, Circularity Metrics, and Aggregated Installation Risk Assessment of the Commercialized Cohort

This section evaluates the multi-dimensional feasibility of the mapped prefabricated solutions by analyzing their usage compatibility, operational applicability, and circular economy performance. Furthermore, it integrates a quantitative assessment of the cumulative technical requirements and installation risk factors that govern the deployment, transportation, and connection phases on legacy building substrates, providing a realistic boundary check for their large-scale urban implementation.

4.4.1. Compatibility, Applicability, Circularity, and Performance Co-Benefits

The systematic tracking of physical applicability thresholds, technical risk constraints, and circular economy indicators across the 26 commercially available solutions provides a pragmatic reality check for the deployment of industrialized retrofits. As analyzed in Figure 8, the database registers a massive industrial prioritization of cross-sectoral versatility. Within the Single-Function Envelope Systems (Façade & Roof) macro-category, a dominant cohort of 17 solutions is engineered to simultaneously target both residential and non-residential applications, whereas a minor baseline of only 2 entries remains strictly limited to residential host buildings. Shifting the focus to Multi-Functional Integrated Systems (Façade & Roof) family, a complementary trend is observed: 5 active configurations are successfully designed for dual-use deployment across both sectors, while a restricted niche of 2 solutions is strictly tailored for residential requirements.

Usage Compatibility

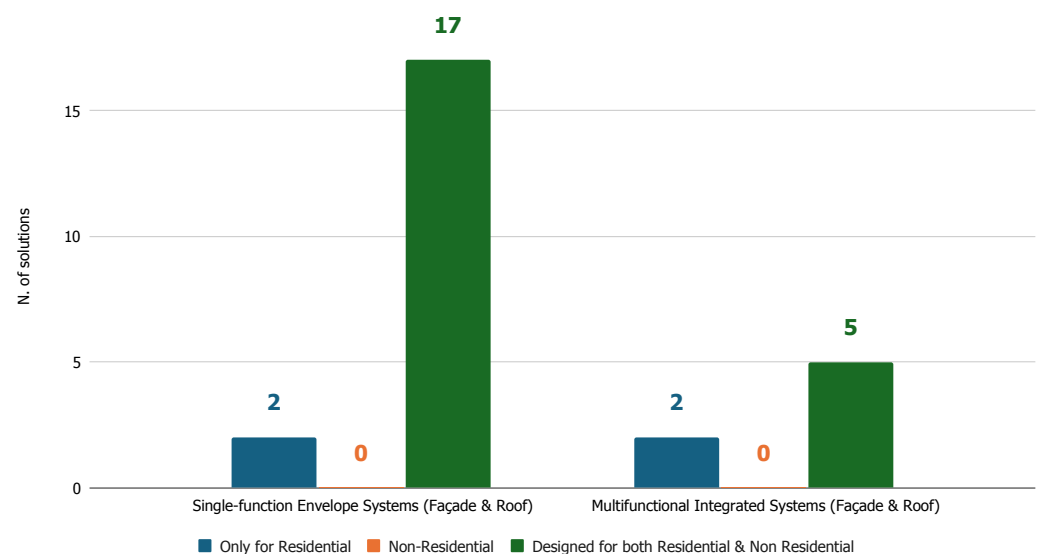


Figure 8. Usage compatibility mapping of commercially available solutions across the primary taxonomic families (data source: BARRIO database, compiled as of March 2025).

From a decarbonization perspective, the high share of dual-use systems (representing exactly 84.6% of the validated database entries) is highly beneficial, providing a flexible and versatile technical baseline for scaling up residential and general deep retrofits. However, the complete absence of specialized non-residential systems represents a distinct bottleneck for highly complex public and commercial assets (such as schools, university complexes, and hospitals). These non-residential structures face significantly higher structural fire resistance mandates, specialized acoustic separation requirements, and intense, localized aerodynamic wind shear profiles (SR2) that standard, generic-use over-cladding components cannot easily accommodate. Traditional anchoring sub-frames are frequently

structurally inadequate to absorb these dynamic forces without massive, expensive structural reinforcements on the host building's legacy frames (SR1). Stricter municipal building codes and safety regulations (BCR1) regarding vertical fire propagation on tall façades further restrict the use of affordable synthetic insulation materials, effectively creating an implementation bottleneck within the non-residential urban market despite the nominal versatility of the systems.

The market orientation of these prefabricated solutions, distinguishing between systems engineered exclusively for retrofitting and those versatile enough for greenfield projects, is illustrated by the applicability profiles in Figure 9. Within the analyzed dataset, the distribution reveals a strategic division between targeted retrofitting specialization and cross-market versatility. Regarding Single-function Envelope Systems (Façade & Roof), a minor segment of 3 solutions is marketed exclusively as dedicated renovation kits, whereas a substantial manufacturing majority of 16 entries exhibits dual-use versatility, demonstrating structural compatibility across both greenfield works and legacy renewal tasks. Conversely, when shifting the focus to Multi-Functional Integrated Systems (Façade & Roof) family, a more balanced engineering distribution is observed: 4 active technologies are restricted strictly to existing building envelopes, while 3 configurations are configured to serve both technical scopes seamlessly.

Applicability to renovation/new construction

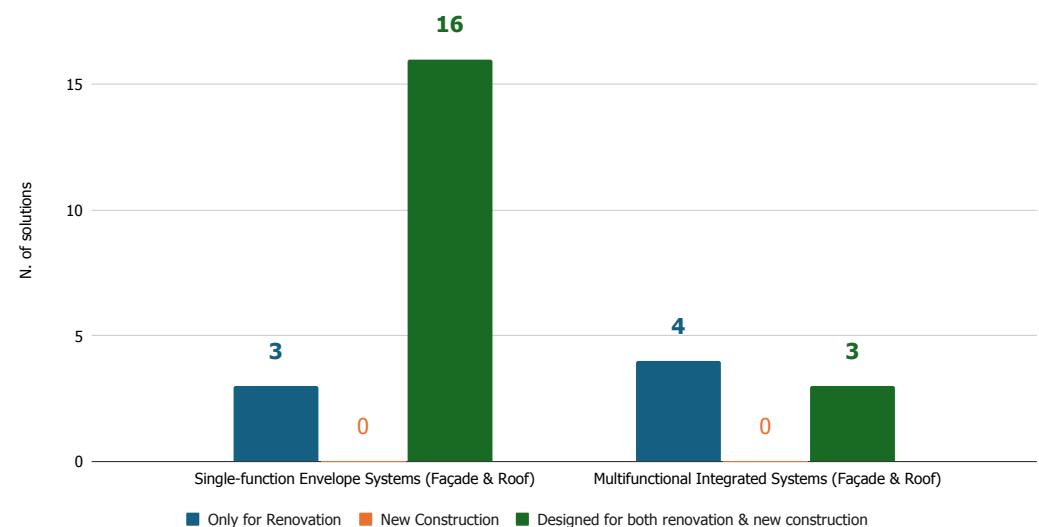


Figure 9. Operational applicability breakdown of commercially available solutions, distinguishing between dedicated renovation kits and dual-use structural systems (data source: BARRIO database, compiled as of March 2025).

This high degree of dual applicability indicates that while the commercial systems are structurally engineered to absorb as-built geometric deficits and structural misalignments on aging substrates, their off-site manufacturing workflows successfully retain the dimensional standardization and modular coordination required to integrate into new construction workflows without forcing assembly or design disruptions.

Crucially, off-the-shelf prefabricated offerings optimized exclusively for greenfield new construction applications are completely absent from the analyzed commercial catalogs, leaving this specific market classification completely unpopulated across both taxonomic families examined. In new construction frameworks, industrialized components must compete directly with hyper-optimized, low-cost traditional methods, such as cast-in-place

concrete or standard lightweight drywall framing, where the financial margins of advanced off-site components are significantly tighter and harder to justify to developers.

Conversely, within deep retrofitting scenarios, the capacity of these pre-assembled panels to compress installation timelines from months to days, minimize costly occupant relocation, and consolidate multiple functional layers into a single crane-assisted hoisting operation provides the necessary premium margin to offset higher upfront manufacturing capital investments. Furthermore, for the subsets designated exclusively for legacy renovations, the engineering focus shifts entirely away from standard industrial modularity toward high-tolerance structural interfaces. These configurations rely on adjustable punctiform anchoring sub-frames, telescoping thermal-bridge-free brackets, and specialized edge junction detailing engineered specifically to absorb the extreme out-of-plumb deviations, structural settlements, and material degradations unique to post-war European building substrates.

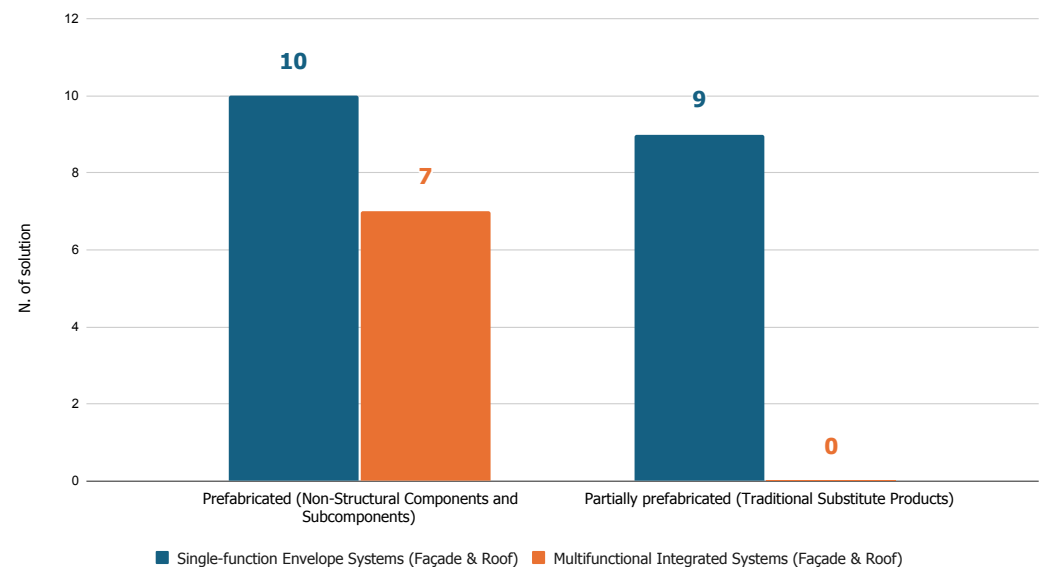
The structural typology and circular economy disclosures of these commercial systems, mapping Modern Methods of Construction (MMC) profiles alongside material resource claims, are detailed in Figure 10a. Within the analyzed dataset, the distribution reveals a clear divide in manufacturing complexity. Regarding the Single-Function Envelope Systems (Façade & Roof) macro-category, a slight majority of 10 solutions is manufactured as fully prefabricated, non-structural components. Conversely, a substantial baseline of 9 entries consists of partially prefabricated, traditional substitute products, reflecting a common industry practice of adapting conventional, wet-applied building insulation materials into dry, panelized kits designed to be mechanically fastened on-site, thereby lowering initial manufacturing complexity. Shifting the focus to Multi-Functional Integrated Systems (Façade & Roof) family, a complete structural polarization is observed: all 7 active solutions are engineered exclusively as fully prefabricated, non-structural components. Crucially, partially prefabricated solutions are completely absent from this active category, leaving this specific classification entirely unpopulated. This absolute division is dictated by rigorous engineering requirements. Integrating active mechanical services, localized ventilation channels, and electrical wiring harnesses within an industrialized building envelope requires millimetric factory tolerances, continuous quality control, and clean indoor assembly environments that traditional substitute products adapted on-site simply cannot provide. Consequently, this distribution establishes that the vast majority of the commercialized sample—representing exactly 65.4% of the validated database entries—relies on fully prefabricated structural workflows.

The evaluation of the circular economy dimension (Figure 10b) tracks the explicit technical disclosures and certified material claims provided within the available product literature, exposing a profound deficit in documented resource transparency and formal green certifications across the commercialized prefabrication sector. Within the Single-Function Envelope Systems (Façade & Roof) macro-category, a dominant cohort of 14 solutions remains entirely dependent on conventional virgin resources. A minor segment of only 3 solutions explicitly documents the integration of certified recycled materials, while a restricted niche of 1 solution incorporates reused materials, and 1 entry targets other circularity features. Shifting the focus to Multi-Functional Integrated Systems (Façade & Roof) family, a complementary constrained trend is observed: 5 active configurations rely on conventional virgin raw materials, while only 1 solution documents the use of recycled materials, and 1 entry targets other circular aspects. Active industrialized offerings incorporating reused materials are absent from the analyzed commercial catalogs.

Overall, this establishes that a dominant 73.1% of the entire validated database remains heavily dependent on virgin resource extraction (such as virgin aluminum claddings, steel

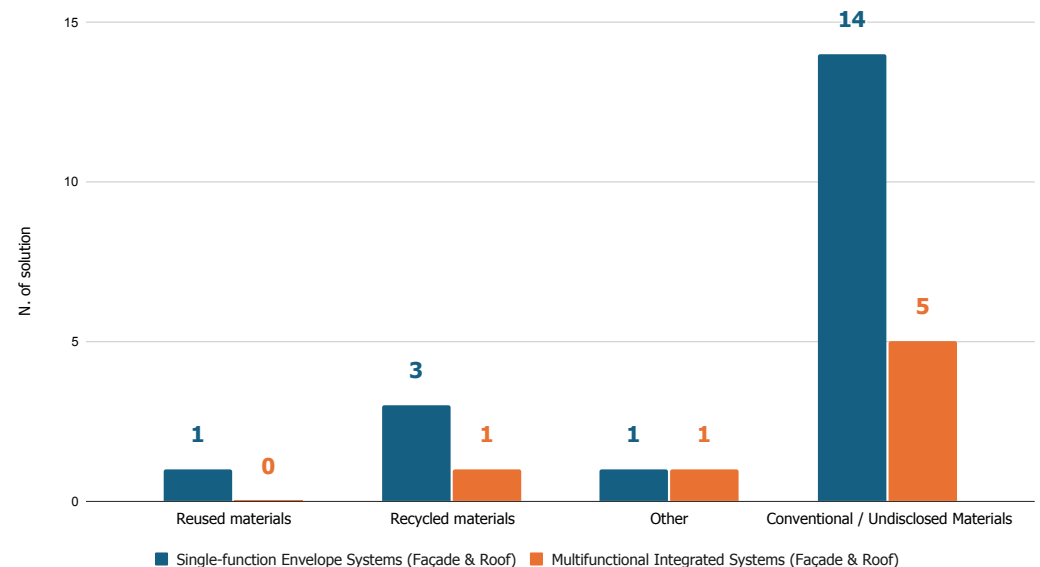
sub-frames, and synthetic polymer insulation), with certified recycled content representing only 15.4% of the total commercial sample.

Type of solution



(a)

Circularity aspects



(b)

Figure 10. Classification of commercially available solutions based on (a) Modern Methods of Construction (MMC) typologies and (b) circular economy material metrics (data source: BARRIO database, compiled as of March 2025).

This material bottleneck is closely linked to the specific insulation matrices selected by manufacturers. The commercialized single-function cohort relies heavily on standardized, cost-effective insulation materials, such as Expanded Polystyrene (EPS), Polyisocyanurate (PIR) boards, and mineral wool slabs. While these synthetic and mineral matrices provide reliable thermal barrier performance and meet fire safety codes, they are highly energy-intensive to produce and represent significant embodied carbon barriers. Conversely, bio-based and renewable insulation matrices (e.g., wood fiber, hemp, or straw) remain

absent from the commercialized sample. This conventional material reliance is dictated by standard manufacturing methods that prioritize immediate thermal and airtightness performance over end-of-life recovery. To meet mandatory energy and acoustic targets, the industry continues to rely heavily on irreversible wet-sealing compounds, chemical bonding agents, and injected polyurethane foams (C&F2). These adhesive practices prevent clean, non-destructive material separation, creating a severe bottleneck for multi-functional active skins where heterogeneous components—such as glass, metal frames, polymers, and electrical wiring—are fused into single monolithic panels. Consequently, the widespread absence of dry joints and reversible mechanical interfaces makes end-of-life recycling technically difficult and restricts the practical adoption of secondary resources across both taxonomic families.

Despite these technical and material boundaries, the descriptive distribution of the broader socio-environmental co-benefits delivered by the available solutions is substantial. As compiled in Figure 11, energy performance improvements and thermal comfort enhancements represent the universal, non-negotiable operational baseline within the audited sample, with both benefits registered by 19 single-function envelope systems and 7 multi-functional integrated configurations. This perfect numerical synchronization confirms that reducing space heating demand and stabilizing indoor radiant temperatures remain the primary market drivers and core technological goals for both passive cladding and active prefabrication strategies.

Improvements brought by the solutions

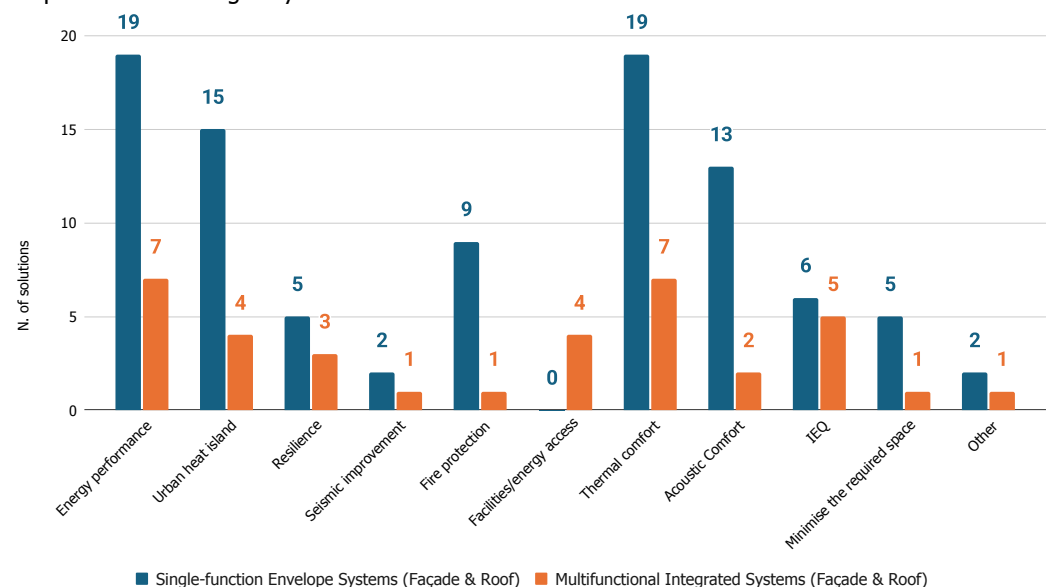


Figure 11. Systematic mapping of technical, environmental, and socio-economic performance improvements brought by the mapped solutions (data source: BARRIO database, compiled as of March 2025).

Beyond these core thermal metrics, the dataset highlights a strong emphasis on localized indoor environmental quality and structural safety. Acoustic comfort features are documented in 13 available single-function envelope systems and 2 multi-functional modules, reflecting the inherent noise-attenuation co-benefits of thick, dense insulation cores (such as mineral wool slabs) when integrated into industrialized vertical façade configurations. Concurrently, indoor environmental quality (IEQ) optimizations—primarily targeting humidity stabilization, enhanced filtration paths, and surface condensation mitigation—are consistently registered across 6 single-function and 5 active integrated systems. Fire protection safeguards are also highly represented, certified or explicitly addressed in 9 single-function layouts and a single active module, emphasizing the critical regula-

tory compliance required to satisfy vertical flame-spread standards on mid-to-high-rise residential structures before commercialization.

Significantly, rather than projecting macro-market trends, the sample distribution reflects a targeted integration of urban climate resilience features among recent manufacturing designs. Urban heat island mitigation—primarily delivered through highly reflective cool-roof coatings, ventilated cavity designs, or light-colored façade cladding—is actively addressed by 15 single-function systems and 4 active multi-functional units. In contrast, structural and seismic resilience characteristics remain more restricted, with general resilience considerations embedded in 5 single-function and 3 active configurations, while dedicated, code-compliant seismic improvement is integrated into only 2 single-function systems and a single multi-functional module. This lower frequency reflects the steep engineering, weight, and cost barriers associated with implementing structural retrofits that must mechanically transfer horizontal shear forces back to the host building's primary reinforced concrete or masonry frame.

A particularly telling functional divide is observed regarding localized infrastructure integration: while single-function envelope systems completely lack integrated facilities or energy access features—leaving this specific operational benefit entirely unpopulated and unrepresented within the passive cohort—a specialized group of 4 multi-functional integrated systems successfully incorporates these technical distribution layers. This discrepancy is industrially logical, as passive panels are strictly limited to thermal protection, whereas active skins are specifically engineered to host integrated ductwork, piping, and electrical wiring harnesses. Finally, the capacity of prefabricated kits to minimize the physical space required on-site during installation is highlighted as an advantage by 5 single-function systems and a single active integrated system, while the remaining minor parameters account for 2 single-function and a single multi-functional system categorized under other benefits.

4.4.2. Aggregated Risk and Technical Requirement Frequency Analysis

To map the systemic operational friction points governing industrialized retrofits across the built environment, Figure 12 compiles the technical risk codes and installation requirements validated across the cohort of $N = 26$ commercially available technologies. These data points represent descriptive cumulative counts extracted from the binary compliance matrix mapped for the commercial portfolio, operating as explicit indicators of structural, logistical, and regulatory complexity.

To quantify the real-world impact of these constraints and ensure full methodological transparency, this study evaluates the Prevalence Rate (%) of each constraint within the commercial cohort. This metric represents the absolute percentage of commercialized solutions (out of the constant sample size $N = 26$) that actively trigger or require compliance with a specific risk indicator or installation requirement. It is calculated through the following standalone formulation:

$$\text{Prevalence Rate (\%)} = \frac{\text{Commercial Solutions Affected by a Specific Indicator}}{\text{Total Commercialized Sample}} \times 100$$

Under this mathematical framework, the physical meaning of the frequency values (e.g., 20 for BCR1) translates directly into a standardized market availability threshold (e.g., 76.9% of the commercial cohort). This provides an objective baseline to evaluate how deeply certain technical and regulatory friction points affect off-the-shelf industrial solutions.

Technical Risk Codes & Requirements

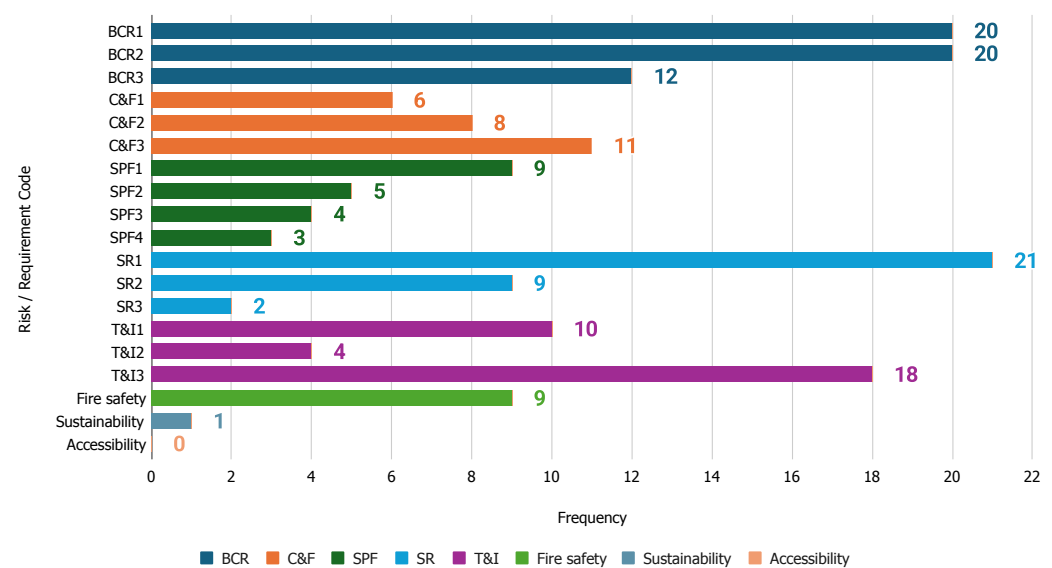


Figure 12. Quantitative frequency distribution of technical risk codes and installation requirements across the cohort of $N = 26$ commercialized technologies. (Frequencies represent the absolute count of commercial solutions actively triggering each constraint. Data source: BARRIO database, compiled as of March 2025).

This mapping analysis exposes that regulatory alignment, installation logistics, and host-substrate safety represent the primary boundaries to commercial deployment. Within the regulatory domain, the severe impact of building codes and safety regulations is explicitly quantified by a peak prevalence rate of 76.9%, with compliance with both local building codes (BCR1) and fire safety or acoustic performance standards (BCR2) each affecting 20 out of 26 commercial solutions. These are followed by administrative permitting procedures (BCR3) at 46.2% (12 solutions). For the structural domain, ensuring host frame load-bearing capacity (SR1) registers a dominant prevalence rate of 80.8% (21 solutions), confirming that substrate dead-load capacity is a near-universal engineering stress factor, while wind-shear resistance profiles (SR2) and seismic configuration boundaries (SR3) constrain 34.6% (9 solutions) and 7.7% (2 solutions), respectively.

Logistical and installation boundaries are equally polarized: the critical shortage of certified, highly skilled assembly labor (T&I3) represents a severe market bottleneck affecting 69.2% of the cohort (18 solutions), followed by physical site access limitations (T&I1) at 38.5% (10 solutions), and hoisting machinery deployment constraints (T&I2) at 15.4% (4 solutions). For connection and finishing requirements, custom architectural finishing workflows (C&F3) lead with a prevalence rate of 42.3% (11 occurrences), followed by interfacial insulation sealing and weatherproofing techniques (C&F2) at 30.8% (8 occurrences), and final network utility connections (C&F1) at 23.1% (6 occurrences). Foundational ground parameters (SPF1–SPF4) maintain a lower but steady impact range, led by geotechnical site preparation (SPF1) with a prevalence of 34.6% (9 occurrences), substrate leveling (SPF2) at 19.2% (5 occurrences), foundation alignment (SPF3) at 15.4% (4 occurrences), and structural settlement risks (SPF4) at 11.5% (3 occurrences).

Definitively, the transversal performance benchmarks plotted on the right-hand side of Figure 12 highlight cross-cutting qualitative compliance requirements that operate independently of localized site-specific or structural codes. Under this classification, compliance with strict fire safety standards remains an active requirements focus for 34.6% of the available options (9 commercial solutions), while targeted considerations for environmental sustainability represent an emerging requirement with a minor baseline of only 3.8%

(1 occurrence). Crucially, inclusive accessibility considerations are completely unrepresented in current commercial catalogs, leaving this specific indicator entirely unpopulated.

5. Discussion

The empirical findings interpreted in this section provide a pragmatic reality check regarding the scalability of industrialized renovation across the European Union. By shifting the analytical lens from idealized laboratory prototypes to the strict market-ready dataset of 26 commercially available solutions, this discussion answers the primary research questions by highlighting the physical, regulatory, and technical boundaries that off-the-shelf technologies must clear to achieve widespread adoption.

5.1. The Gap Between R&D and Market Uptake

The structural composition of the repository exposes the “valley of death” that paralyzes the transition from academic innovation to commercial viability. While a massive volume of highly sophisticated, multi-system active façades has been developed under intensive European research grants (such as Horizon 2020 frameworks), these technologies remain structurally trapped in the pre-commercial prototyping phase (accounting for 42 entries compiled in Appendix A). Conversely, the actual commercial market analyzed in Section 4.1 is heavily dominated by basic, low-risk passive insulation configurations, with single-function envelope kits thoroughly outnumbering available multi-functional systems (19 available passive solutions versus only 7 active systems).

The empirical data from Sections 4.3 and 4.4 demonstrate that embedding active building service layers—such as complex mechanical HVAC ductwork and Building-Integrated Photovoltaic (BIPV) wiring—directly into prefabricated panel cores generates severe supply chain and operational fragmentation. A major bottleneck lies in the deep technical silo separating the contemporary industry: traditional, craft-based construction firms lack the advanced thermomechanical and electronic engineering know-how required to deploy multi-technological panels, while specialized HVAC manufacturers remain industrially detached from envelope prefabrication and structural tolerance management.

Furthermore, the initial capital expenditure required to establish a fully automated factory line capable of producing these multi-technological panels remains financially prohibitive for manufacturers without a pre-existing, legally aggregated, and guaranteed market demand. This commercial deadlock is reinforced by a severe certification barrier: while a standard passive component follows clear, standardized regulatory compliance pathways, European building control bodies currently lack a unified framework to certify or guarantee a composite component that simultaneously acts as a structural envelope wall, a localized ventilation heater, and a decentralized power plant.

5.2. Overcoming Geometric and Structural Barriers

The physical applicability thresholds and structural constraints mapped in Section 4.4 expose the deep mismatch between standardized industrial manufacturing and the severe morphological heterogeneity of the European housing stock. The large-scale 2D prefabricated panels currently available on the commercial market are highly optimized for the homogeneous, box-like multi-family residential blocks and industrialized concrete panel typologies characteristic of Northern and Western European post-war suburbs. Conversely, these rigid commercial systems encounter severe physical implementation barriers when deployed within Southern European and Mediterranean urban cores, which are dominated by historic, highly irregular masonry structures, prominent projecting balconies, extensive out-of-plumb wall deviations, and strict architectural heritage constraints.

To successfully scale the Renovation Wave without triggering widespread field failures, the industrial manufacturing trajectory must move away from massive, unyielding rigid panels that demand perfectly square host substrates. The commercial market must actively pivot toward the development of adaptive anchoring sub-frames and flexible structural interfaces. These engineered sub-frames must be capable of absorbing major as-built geometric deficits and structural misalignments, mechanically compensating for tolerances spanning several centimeters while ensuring safe load distribution (SR1) and mitigating high-altitude wind-shear profiles (SR2) without requiring destructive, time-consuming on-site adjustments.

5.3. *The Circularity and Co-Benefits Challenge*

The material and circularity metrics extracted from the market-ready dataset reveal a significant material bottleneck across the commercialized prefabrication sector. Current off-the-shelf prefabricated panels have been almost exclusively engineered to maximize operational efficiency—focusing strictly on rapid thermal transmittance reductions to cut tenant energy bills—while completely ignoring the Embodied Carbon footprint of their constituent materials. As a result, 73.1% of the commercially available solutions rely entirely on conventional virgin resources (such as virgin aluminum claddings, steel sub-frames, and synthetic polymer insulation), leaving documented recycled content (15.4%) and component reuse (3.8%) at a marginal baseline.

This structural neglect will inevitably transform into a massive commercial and regulatory obstacle under the newly recast Energy Performance of Buildings Directive (EPBD). The updated European mandates require a mandatory, systematic calculation of the Life-Cycle Global Warming Potential (GWP) for renovation works, meaning that the unconstrained use of petrochemical synthetic foams (EPS, PIR) and virgin metals within commercial panels will soon face severe carbon-tax penalties and legal limits.

To maintain market viability, future commercial technologies must undergo a radical material transformation, turning toward advanced engineered wood layouts (timber-frames), regenerative bio-based insulation cores (such as wood fiber, hemp, or straw matrices), and the implementation of reversible mechanical dry-joint connections. This requires transitioning away from irreversible wet chemical bonding and polyurethane sealants (C&F2) toward dry mechanical interfaces, ensuring that commercial components can be cleanly unbolted, sorted, and recirculated at the end of their operational life cycle.

5.4. *The Unavoidable Need for Digital Integration*

For the sake of methodological completeness, it must be emphasized that while the primary focus of this manuscript evaluates physical hardware configurations categorized under the Solutions and Technologies (ST) nomenclature, a parallel mapping campaign was systematically executed for digital platforms and software architectures using an identical taxonomy. This parallel tracking is scientifically vital because the physical, geometric, and structural friction points detailed in Section 4 can only be overcome by systematically pairing the physical hardware panels with intensive, integrated digital workflows.

The realization of cost-effective “Mass Customization” within a highly fragmented building stock is inherently impossible without a digital thread connecting the cantiere to the factory floor. The deployment of high-precision laser-scanner surveys, Building Information Modeling (BIM), and dynamic Digital Twins represents the unavoidable technological bridge required to scale this industry. Without a rigorous, automated Scan-to-BIM data pipeline, it is mathematically impossible to prefabricate a large-scale panel off-site that fits the irregular, distorted millimetric reality of a 60-year-old legacy building, ensuring that digital integration is not a luxury but a structural prerequisite for industrialized retrofitting.

5.5. Comparison with the Existing Literature

The methodological framework developed in this study provides a crucial calibration loop when evaluated against the broader body of academic and institutional literature. Unlike previous mappings such as the BPIE reports, which primarily focused on the potential energy savings of industrialized retrofits, this taxonomy provides a reality check by highlighting the strict geometric and usage constraints that currently bottleneck the deployment of these technologies.

While baseline international energy models often treat the European building stock as a generic, unconstrained surface ready to absorb standardization, this mapping analysis grounds these macro-level projections within micro-level physical boundaries. By quantifying the severe impact of local building codes (affecting 76.9% of the commercialized systems), structural substrate limitations (affecting 80.8% of the cohort), and logistical access constraints (affecting 69.2% of the mapped solutions), this research exposes the operational friction zones that must be systematically dismantled by policymakers and product designers to translate theoretical European carbon neutrality targets into successful, non-disruptive urban execution.

6. Conclusions

6.1. Core Synthesis and Policy Recommendations

The systematic mapping and taxonomic classification executed through the BAR-RIO|PREFAB MAPPING_X2 framework provide an empirical reality check on the current industrial capacity of deep renovation across the European Union. While the total mapping campaign captured 68 physical solutions to document the broader state of the art, isolating the 26 market-ready systems for quantitative analysis exposes a distinct, structural “two-speed” Southern European market. On one speed, the commercial ecosystem is mature and structurally prepared for passive building envelope retrofits, primarily utilizing standardized 2D prefabricated insulation modules. On the slower speed, the commercial market remains highly limited regarding multi-functional integrated systems that embed active HVAC networks and renewable energy generation, with the vast majority of these advanced multi-technological configurations remaining locked in the pre-commercial research and development (R&D) phase and relegated to Appendix A. The primary industrial bottlenecks preventing off-the-shelf solutions from scaling are not tied to theoretical energy performance optimizations but rather to real-world manufacturing supply chain fragmentation, high upfront capital investments, institutional certification gaps, and physical constructability limits on-site. Furthermore, this study exposes a critical “circularity paradox”: while aiming for deep energy-saving performance, the commercial market remains heavily reliant on virgin, carbon-intensive synthetic materials, severely lacking the explicit quantitative reporting and reversible dry-joint connections necessary to meet the upcoming EPBD whole-life carbon mandates. To accelerate the deployment of industrialized deep renovation and support the market penetration of off-the-shelf prefabricated technologies, the following policy interventions are recommended:

- **Standardization and Open Interface Protocols:** The European Commission, in coordination with standardization bodies such as CEN and ISO, must establish harmonized, open-source mechanical and electrical interface protocols for off-site components. Standardizing connection nodes is critical to ensure interoperability, allowing a commercially available prefabricated façade system from Manufacturer A to seamlessly and securely couple with a decentralized technical pod or mechanical ventilation unit from Manufacturer B, eliminating vendor lock-in risks.

- **Green Public Procurement (GPP) as a Market Catalyst:** Public contracting authorities across Europe must act as strategic “first movers” to mitigate industrial financial risks for market-ready systems. Incorporating strict mandates for off-site prefabricated construction methods within public tenders—specifically targeting the large-scale renovation of public social housing stocks—will generate the predictable, aggregated market demand necessary for manufacturers to confidently invest in automated factory infrastructures and lower unit production costs.
- **Regulatory Flexibility and Permitting Derogations:** Local building codes and municipal urban planning ordinances must be updated to accommodate the physical realities of commercialized industrialized retrofits. Since high-performance external façade panels and structural seismic exoskeletons inherently increase wall thicknesses (typically by 15 to 35 cm), national and local permitting frameworks should grant automatic legal derogations regarding property boundaries, minimum building distances, and volume constraints when these additions are strictly required for certified energy and structural retrofits.
- **Promoting Circular Materials through Targeted Incentives:** To resolve the verified circularity bottleneck and transition away from virgin synthetic resources, public financial incentives for energy renovations must evolve. Funding schemes should explicitly reward the integration of certified recycled or bio-based materials and the use of reversible, dry-joint mechanical connections instead of irreversible wet-applied chemical sealants. This directly aligns market subsidies with the physical parameters required for end-of-life recovery, shifting the industrial focus from mere operational energy savings to holistic resource efficiency.

6.2. Limitations and Future Research

A distinct methodological limitation of this study concerns the geographical distribution of the harvested sample, which directly influences the composition of the commercialized dataset. As stated, the primary data collection track—consisting of direct expert consultations and on-the-ground market surveys—was inherently tied to the localized industrial networks of the BARRIO consortium partners. Therefore, while secondary literature screenings covered broader EU pilot projects to establish a technological baseline, the final repository exhibits a physiological and intentional predominance of technologies originating from Southern Europe, most notably Italy and Spain. This confirms that the results must be interpreted as a targeted supply-side overview of the Mediterranean context rather than an absolute generalization for the entire European building stock.

While this study establishes an essential baseline by focusing its analytical lens on immediately procurable commercial technologies, it represents only the foundational step toward a comprehensive decision-making framework. The next phase of this research will focus on the operational development, mathematical calibration, and multi-country application of the Prefabrication Readiness Index (PRI). Building directly upon the empirical variables and operational risk codes identified across the commercial dataset in this paper, the PRI will be structured as a comprehensive multi-criteria decision-making scoring matrix. This index will integrate technical, financial, social, and regulatory vectors to quantitatively evaluate the specific compatibility, scalability, and market bankability of available prefabricated solutions against diverse, real-world urban retrofit scenarios across the European built environment.

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Appendix A

This appendix presents the comprehensive repository of the 68 technological prefabricated solutions mapped within the BARRIO|PREFAB MAPPING_X2 relational database. To ensure systematic data retrieval and cross-referencing, the dataset is structured into two complementary matrices.

Appendix A.1. Master Inventory and Commercial Readiness Classification

Table A1 presents the comprehensive master inventory of the 68 audited physical hardware solutions mapped within the “BARRIO|PREFAB MAPPING_X2” framework. To visually highlight the structural polarization and the Southern European market dynamics analyzed in the main text, the dataset rows are systematically segregated into two distinct, mutually exclusive sub-cohorts based on their commercial readiness. The matrix maps each unique identification code (ST—Solutions and Technologies nomenclature) across the functional categories of the developed taxonomy, distinguishing between passive single-function envelopes, active multi-functional integrated systems, and stand-alone technical installations for both façade and roof architectures. This organized classification establishes a rigorous baseline, separating the 26 immediately procurable, off-the-shelf industrial offerings from the 42 pre-commercial research prototypes born within EU-funded pilot frameworks.

Table A1. Cross-checking matrix of technological prefabricated solutions categorized by market readiness.

ID Code	Single-Function Envelope Systems (Façade & Roof)	Multi-Functional Integrated Systems (Façade & Roof)	Stand-Alone Installations
Commercially Available Solutions (Market-Ready Sub-Cohort)			
ST009		✓	
ST010	✓		
ST012		✓	
ST013		✓	
ST017		✓	
ST019		✓	
ST020	✓		
ST026	✓		
ST032		✓	
ST034		✓	
ST036	✓		
ST037	✓		
ST038	✓		
ST041	✓		
ST042	✓		
ST046	✓		
ST047	✓		
ST048	✓		
ST049	✓		
ST050	✓		
ST051	✓		
ST052	✓		
ST053	✓		
ST056	✓		
ST057	✓		
ST058	✓		
Pre-Commercial Research Prototypes (R&D / Concept Sub-Cohort)			
ST001	✓		
ST002		✓	
ST003		✓	
ST004			✓
ST005			✓
ST006		✓	
ST007	✓		
ST008		✓	
ST011		✓	
ST014		✓	
ST015		✓	
ST016	✓		
ST018		✓	
ST021			✓
ST022			✓
ST024		✓	
ST025		✓	
ST027		✓	
ST028		✓	
ST029		✓	
ST030		✓	
ST033		✓	
ST035	✓		
ST039		✓	
ST043		✓	
ST044		✓	
ST045		✓	
ST054	✓		
ST055		✓	
ST059		✓	
ST061	✓		
ST062	✓		
ST063		✓	
ST064	✓		
ST065		✓	
ST066			✓
ST067	✓		
ST068		✓	

Table A1. *Cont.*

ID Code	Single-Function Envelope Systems (Façade & Roof)	Multi-Functional Integrated Systems (Façade & Roof)	Stand-Alone Installations
Pre-Commercial Research Prototypes (R&D / Concept Sub-Cohort)			
ST069		✓	
ST070		✓	
ST071		✓	
ST072	✓		

The ✓ symbol indicates whether a product belongs to one technology class rather than another.

Appendix A.2. Boundary Risks and Technical Requirements Matrix

The evaluation of construction, logistical, and regulatory friction points across the mapped dataset is structured through two complementary components. First, Table A2 establishes a comprehensive nomenclature key, detailing the exact operational definitions, physical thresholds, and specific risk boundaries identified during the risk-mapping and compliance assessment phase. Second, Table A3 operationalizes this granular taxonomy into a full multi-criteria boolean cross-checking matrix, mapping both the 26 market-ready commercial solutions and the 42 pre-commercial research prototypes against the complete sequence of standardized parameters. By intersecting the unique technological configuration of each module with critical on-site realities—spanning from geotechnical site preparation to complex multi-jurisdictional fire safety compliance—this dual mapping environment exposes the true boundaries dictating scalable deployment within the heterogeneous European building stock. Consequently, it shifts the evaluation paradigm from idealized laboratory conditions to the practical constraints of occupied, legacy real estate, ensuring full analytical self-sufficiency and eliminating repetitive, inefficient cross-referencing with the theoretical sections of the main text.

Table A2. Nomenclature key and operational descriptions of audited internal risk codes.

Code	Technical Description & Specific Risk Boundaries
SPF Site Preparation and Foundation	
SPF1	Geotechnical Survey: soil condition and bearing capacity evaluation to determine subsurface parameters and ensure long-term foundation stability.
SPF2	Grading and Leveling: ground earthworks and preparation to create an even, stable base required for structural component alignment.
SPF3	Foundation Type: selection of concrete slab-on-grade, pier and beam, or basement layouts based on geotechnical surveys and local codes.
SPF4	Utility Connections (Prep): pre-installation audit of readily accessible on-site water, electricity, and sewage hookups.
BCR Building Codes and Regulations	
BCR1	Local Building Codes: mandatory compliance with regional building regulations governing systemic safety, structural integrity, and energy efficiency.
BCR2	Permits: procurement of necessary administrative building permits to legalize installation and allow multi-stage inspections.
BCR3	Zoning Regulations: verification of land-use alignment and restriction compliance to avoid property boundaries and zoning conflicts.
SR Structural Requirements	
SR1	Load-Bearing Capacity: engineering check of host structures and foundations to withstand dead weights, snow, wind, and occupancy live loads.
SR2	Wind Resistance: aerodynamic structural design tailored to absorb local geographic wind load profiles and high-altitude shear forces.
SR3	Seismic Design: structural compliance and dynamic engineering criteria required for building integrity in earthquake-prone zones.

Table A2. Cont.

Code	Technical Description & Specific Risk Boundaries
T&I Transportation and Installation	
T&I1	Access to the Site: road, driveway, and site boundary adequacy for maneuvering heavy logistics and large delivery vehicles.
T&I2	Crane or Lifting Equipment: logistics and safety requirements for deploying heavy hoisting machinery during component assembly.
T&I3	Skilled Labor: requirement for experienced DfMA installers to guarantee quality standards, tolerance absorption, and safety protocols.
C&F Connections and Finishing	
C&F1	Utility Connections (Final): functional execution of final on-site utility network integrations (water, power, sewage).
C&F2	Insulation and Weatherproofing: envelope sealing and jointing techniques implemented to mitigate thermal bridging and atmospheric infiltration.
C&F3	Interior and Exterior Finishes: execution of final architectural layers (drywall, painting, siding, flooring) to meet aesthetic targets.
Additional Transversal Considerations	
Fire safety	Fire Safety: integration of fire-resistant materials, standardized smoke detectors, and structural protection or sprinkler systems.
Sustainability	Sustainability: strategic deployment of recycled or renewable resources combined with low life-cycle environmental impact design.
Accessibility	Accessibility: design and execution compliance with universal inclusive accessibility standards for people with disabilities.

Table A3. Cross-checking boolean matrix of boundary risks and technical requirements across the audited dataset.

ID Code	SPF1	SPF2	SPF3	SPF4	BCR1	BCR2	BCR3	SR1	SR2	SR3	T&I1	T&I2	T&I3	C&F1	C&F2	C&F3	Fire safety	Sustainability	Accessibility
Commercially Available Solutions (Market-Ready Sub-Cohort)																			
ST009																			
ST010																			
ST012																			
ST013	✓		✓	✓	✓	✓		✓		✓	✓		✓	✓	✓				
ST017	✓							✓					✓						
ST019				✓	✓	✓		✓	✓				✓		✓		✓		
ST020					✓	✓		✓	✓				✓		✓				
ST026	✓	✓			✓	✓		✓	✓				✓	✓	✓				
ST032	✓	✓			✓	✓		✓	✓		✓		✓	✓	✓				
ST034	✓				✓	✓	✓	✓	✓		✓		✓	✓					
ST036					✓	✓		✓			✓	✓	✓	✓					
ST037					✓	✓	✓	✓	✓		✓	✓	✓	✓	✓		✓		
ST038																			
ST041																			
ST042	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓
ST046					✓	✓	✓	✓					✓				✓	✓	
ST047					✓	✓	✓	✓					✓				✓	✓	
ST048					✓	✓	✓	✓					✓				✓	✓	
ST049					✓	✓	✓	✓					✓				✓	✓	
ST050					✓	✓	✓	✓					✓				✓	✓	
ST051					✓	✓	✓	✓					✓				✓	✓	
ST052					✓	✓	✓	✓					✓				✓	✓	
ST053					✓	✓	✓	✓	✓		✓	✓					✓	✓	
ST056	✓	✓	✓		✓	✓	✓	✓			✓								
ST057	✓	✓	✓		✓	✓		✓	✓		✓		✓		✓				
ST058	✓				✓	✓		✓			✓		✓		✓				

Table A3. Cont.

ID Code	SPF1	SPF2	SPF3	SPF4	BCR1	BCR2	BCR3	SR1	SR2	SR3	T&I1	T&I2	T&I3	C&F1	C&F2	C&F3	Fire safety	Sustainability	Accessibility
Pre-Commercial Research Prototypes (R&D / Concept Sub-Cohort)																			
ST001					✓			✓							✓				
ST002					✓														
ST003																			
ST004																			
ST005					✓														
ST006		✓		✓	✓			✓		✓		✓			✓				
ST007				✓		✓					✓								
ST008				✓	✓	✓		✓		✓	✓	✓		✓	✓				
ST011																			
ST014	✓	✓		✓	✓	✓		✓	✓	✓	✓			✓	✓				
ST015	✓				✓	✓		✓	✓	✓	✓			✓	✓				
ST016					✓	✓		✓	✓	✓	✓			✓	✓				
ST018					✓	✓					✓		✓	✓	✓				
ST021				✓	✓	✓		✓			✓		✓	✓	✓				
ST022	✓			✓	✓			✓						✓	✓				
ST024								✓	✓					✓	✓		✓	✓	✓
ST025			✓	✓	✓	✓		✓	✓		✓		✓	✓	✓				
ST027	✓				✓	✓		✓	✓		✓		✓	✓	✓				
ST028	✓		✓		✓			✓	✓				✓	✓	✓				
ST029	✓				✓	✓		✓	✓		✓			✓	✓				
ST030	✓				✓			✓			✓		✓						
ST033	✓	✓	✓		✓	✓	✓	✓			✓		✓						
ST035					✓	✓		✓			✓	✓	✓						
ST039					✓	✓	✓	✓	✓		✓	✓	✓		✓	✓			
ST043					✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		✓	✓	
ST044	✓				✓	✓		✓	✓		✓		✓		✓				
ST045																			
ST054	✓	✓			✓	✓		✓	✓		✓		✓	✓	✓				
ST055	✓				✓	✓		✓	✓				✓	✓	✓				
ST059	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓				
ST061					✓	✓		✓	✓		✓		✓	✓	✓				
ST062	✓	✓			✓			✓	✓		✓			✓					
ST063					✓	✓		✓	✓		✓		✓	✓					
ST064					✓	✓		✓	✓		✓		✓	✓	✓				
ST065				✓	✓	✓	✓	✓			✓	✓	✓	✓	✓				
ST066					✓	✓		✓					✓	✓					
ST067					✓	✓	✓	✓					✓	✓					
ST068					✓	✓	✓	✓			✓	✓	✓	✓					
ST069					✓	✓	✓	✓			✓	✓	✓	✓					
ST070									✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
ST071	✓		✓		✓	✓		✓	✓	✓		✓	✓	✓	✓		✓	✓	✓
ST072					✓	✓		✓	✓			✓	✓	✓	✓		✓		✓

The ✓ indicates which boundary risks and technical requirements have been associated with each technological solution.

Appendix A.3. Technological Trends and Aggregated Insights in Research Prototypes

Given the significant volume and technical heterogeneity of the 42 pre-commercial research prototypes (the R&D sub-cohort), presenting their granular parameters in extensive tabular formats would cause severe layout inflation. This section shifts the focus toward a synthetic, graphical aggregation of the prototype data to expose core innovation frontiers, emerging technological trajectories, and cross-project dynamics of EU-funded consortia.

Appendix A.3.1. Geographical Distribution of the R&D Cohort

In alignment with the updated taxonomic framework, the geographical distribution of the pre-commercial research prototypes reflects the collaborative, multi-partner structure of European funding streams (e.g., Horizon 2020 and Horizon Europe frameworks). To prevent market-interpretation bias, all reported metrics indicate the relative

dataset share—representing the cataloged technological diversity within the R&D sub-cohort—rather than commercial sales volumes, as aggregated in Figures A1–A3:

- **Single-Function Envelope Systems (Façade & Roof) (Figure A1):** The pre-commercial passive trajectory is predominantly led by the Netherlands (25.00%), followed by balanced secondary development nodes in Poland and Spain (12.50% each). The remaining entries within this unified envelope cohort are distributed evenly (6.25% per territorial scale) across Switzerland, Austria, Germany, Latvia, Italy, Norway, Hungary, and overarching European multi-partner frameworks.
- **Multi-Functional Integrated Systems (Façade & Roof) (Figure A2):** This active cohort exhibits a high geopolitical fragmentation driven by multi-national consortia (“Europe-wide”), which capture the largest distinct repository share (14.00%). This is closely followed by active national clusters in Italy (10.0%) and Spain (10.00%). Secondary development tracks are anchored in Germany, the Netherlands, and Norway (8.00% each), supported by baseline R&D contributions from Finland, Greece, and Poland (6.00% each), Hungary (4.00%), and minor localized iterations (2.00% each) across Belgium, Austria, Romania, and other EU partner states.
- **Stand-Alone Installations (Figure A3):** Reflecting the shared cross-border nature of centralized technical unit research, this family displays a perfectly uniform distribution profile (15.4% each) across Norway, Poland, the Netherlands, Hungary, Spain, and European multi-partner frameworks, with Italy representing a baseline minority share (7.7%).

Single-function Envelope Systems (Façade & Roof)

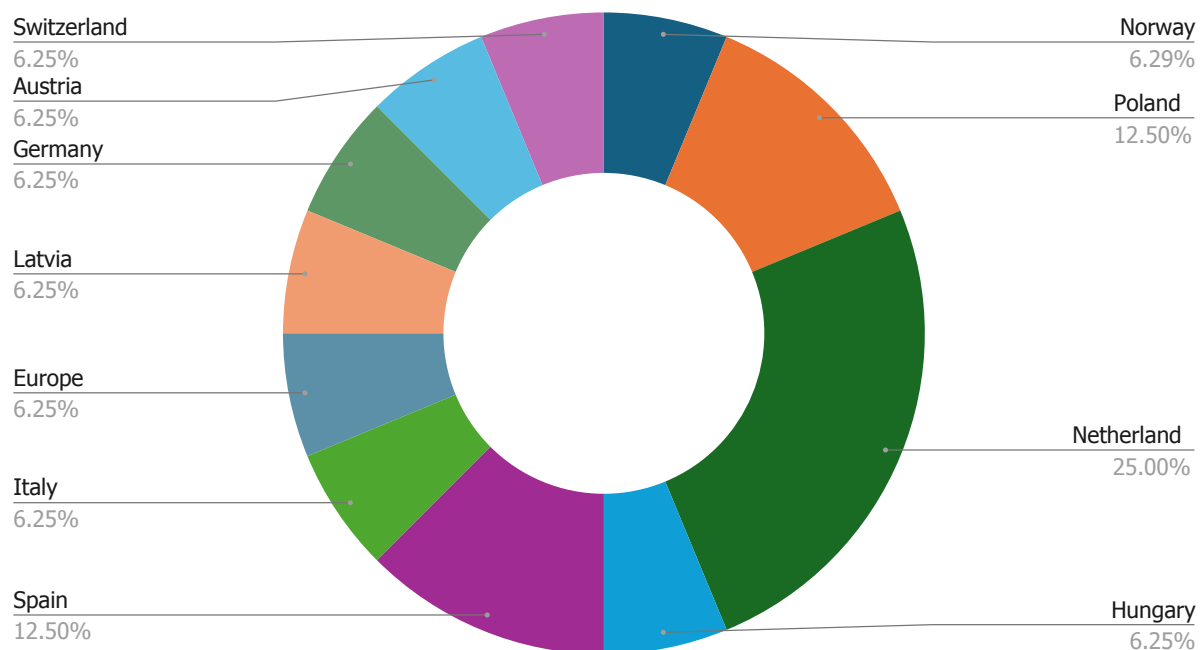


Figure A1. Geographical distribution of primary certified technical validation scales for single-function envelope systems (Façade & Roof) prototypes. (Percentages calculated over total geographic validation records, $N_{\text{val}} = 16$, representing $N = 10$ distinct research prototype systems. Data source: BARRIO database, compiled as of March 2025).

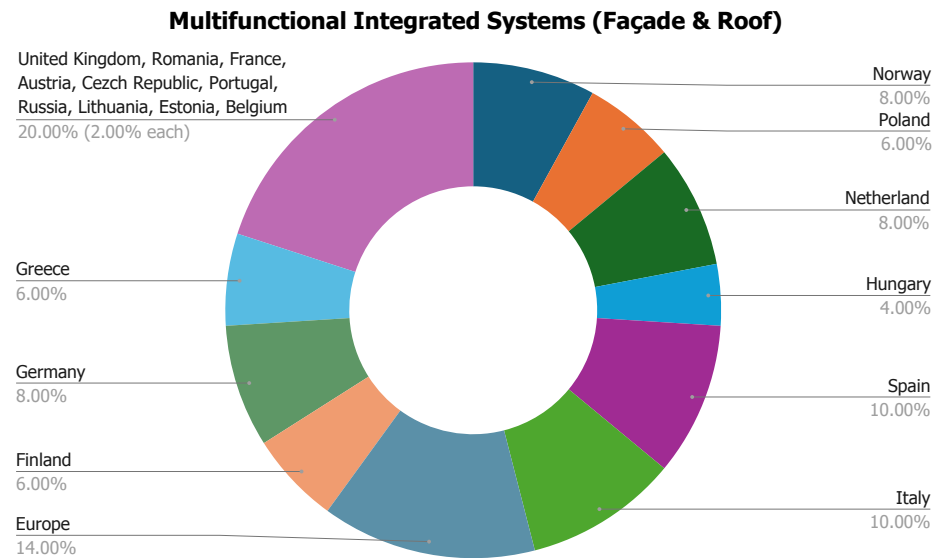


Figure A2. Geographical distribution of primary certified technical validation scales for multifunctional integrated systems (Façade & Roof) prototypes. (Percentages calculated over total geographic validation records, $N_{val} = 50$, representing $N = 27$ distinct research prototype systems. Data source: BARRIO database, compiled as of March 2025).

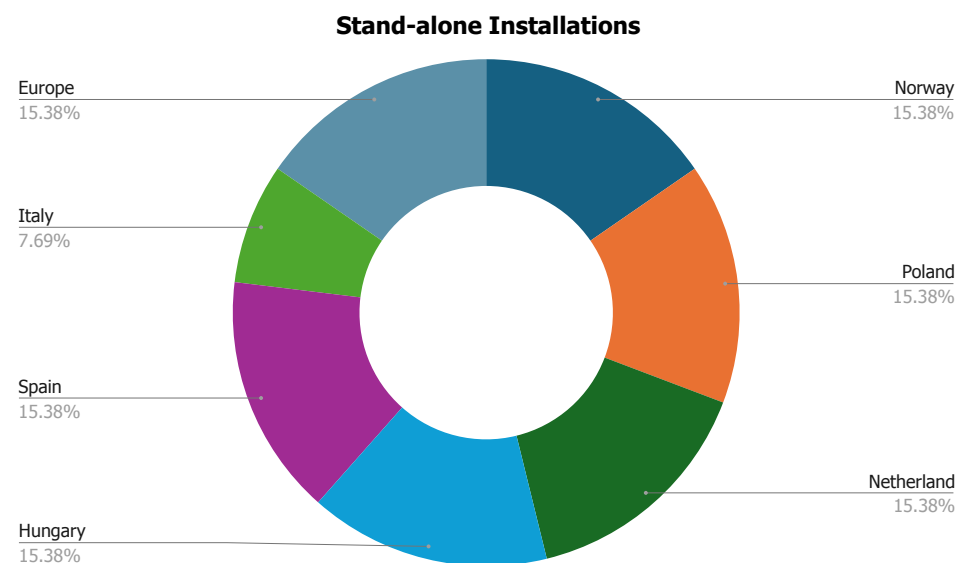


Figure A3. Geographical distribution of primary certified technical validation scales for stand-alone installations prototypes. (Percentages calculated over total geographic validation records, $N_{val} = 13$, representing $N = 5$ distinct research prototype systems. Data source: BARRIO database, compiled as of March 2025).

Appendix A.3.2. Functional Subsystem Integration (Envelope, HVAC, RES) of the R&D Cohort

Deconstructing the internal physical hardware layers of the R&D sub-cohort isolates the technological trends driving next-generation system aggregation, as characterized by the component and subsystem mappings in Figures A4–A6:

- **Envelope Subsystems (Figure A4):** Multi-Functional integrated active variants maximize component multi-layering within the factory core (incorporating 24 wall insulation cores, 18 window kits, and 8 dynamic shading devices) compared to basic passive research configurations, which remain limited to baseline implementations (9 insulation layers, 5 window kits, and 2 shading devices).

- **HVAC Subsystems (Figure A5):** Multi-Functional active building skins thoroughly dominate the decentralized service pipeline, embedding mechanical ventilation with heat recovery (18 instances), localized heating circuits (17), cooling matrices (15), and compact DHW units (7). Conversely, stand-alone Installations focus their industrial configuration primarily on centralized thermal production skids (5 heating and 5 cooling loops), supplemented by minor integrations of secondary water, ventilation, and latent load management layers.
- **RES Harvesting & Storage (Figure A6):** The prototype sector remains heavily solar-centric, with active multi-functional matrices incorporating 16 conventional photovoltaic frame attachments and 14 Building-Integrated Photovoltaic (BIPV) structural skins. Notably, alternative thermal harvesting paths are explored through 9 solar thermal collector arrays within multi-functional frames and 2 within stand-alone pods, while electrical battery skids (1 instance) and alternative aerodynamic options remain underdeveloped across contemporary research designs.

Functionalities - Envelope

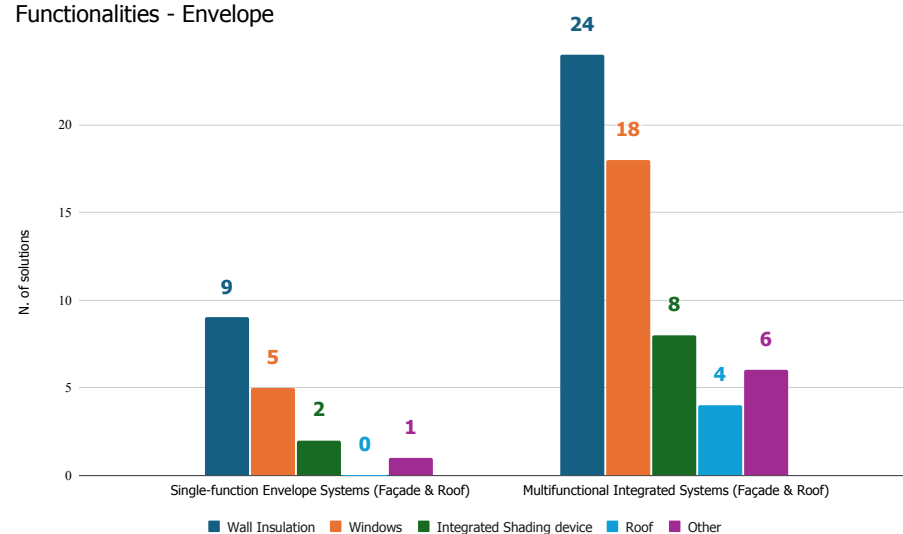


Figure A4. Comprehensive breakdown of embedded envelope functionalities across single-function envelope systems (Façade & Roof) and multi-functional integrated systems (Façade & Roof) research prototypes (data source: BARRIO database, compiled as of March 2025).

Functionalities - HVAC

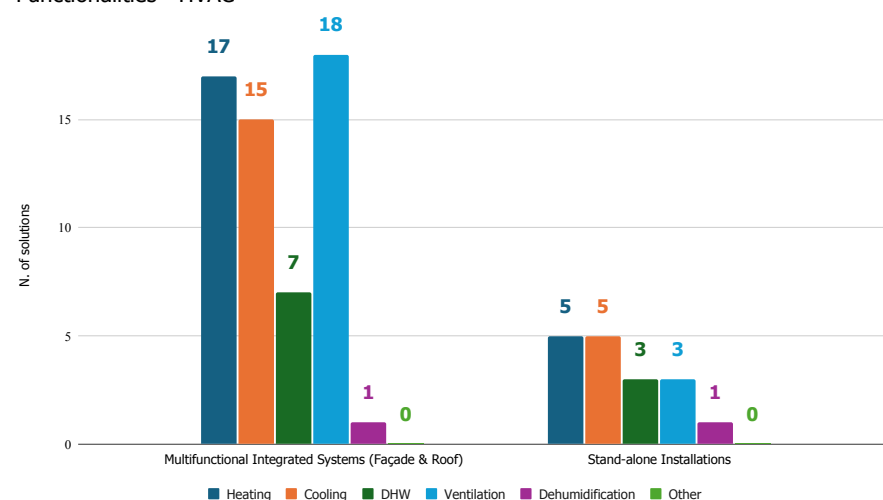


Figure A5. Distribution of embedded HVAC functionalities within multi-functional integrated systems (Façade & Roof) and stand-alone installations research prototypes (data source: BARRIO database, compiled as of March 2025).

Functionalities - RES

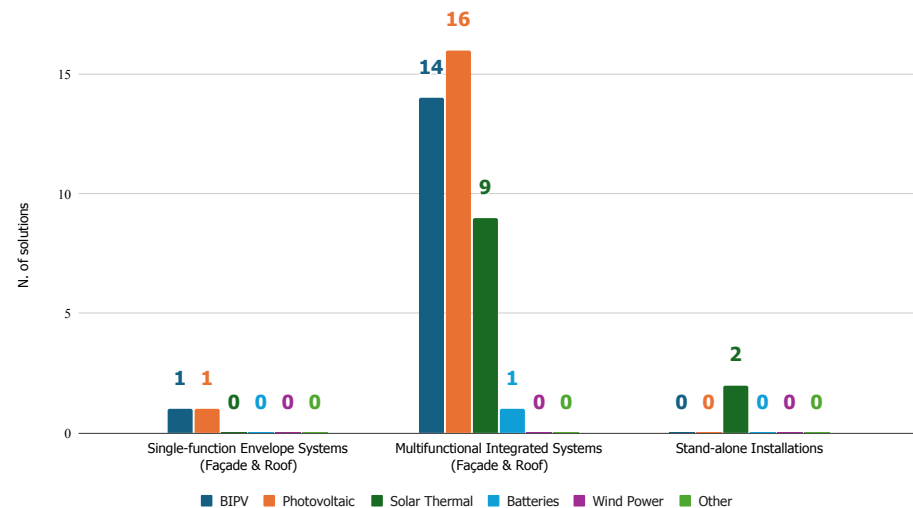


Figure A6. Analysis of renewable energy source (RES) integration patterns across single-function envelope systems (Façade & Roof), multi-functional integrated systems (Façade & Roof), and stand-alone installations research prototypes (data source: BARRIO database, compiled as of March 2025).

Appendix A.3.3. Compatibility, Applicability, Circularity, and Performance Co-Benefits of the R&D Cohort

The multi-dimensional feasibility, structural boundaries, and socio-environmental co-benefits of the pre-commercial research sub-cohort indicate a deliberate R&D orientation toward cross-sectoral adaptability, localized resilience, and the piloting of secondary material loops. To prevent market-interpretation bias, all reported metrics indicate the relative dataset share—representing the cataloged technological diversity within the R&D repository ($N = 42$)—rather than commercial sales volumes, as systematically mapped across Figures A7–A10:

- **Sectorial Compatibility (Figure A7):** The repository confirms a significant design focus on dual-use cross-sectoral versatility, with the vast majority of active configurations (22 multi-functional integrated systems and 3 stand-alone installations) and passive components (6 single-function envelope systems) explicitly engineered to simultaneously clear both residential and non-residential building regulations. Conversely, restricted residential-only applications remain confined to a minor baseline (4 active, 3 passive, and 2 stand-alone systems).
- **Process Application (Figure A8):** Active multi-system kits heavily prioritize legacy renewal infrastructure, with 16 multi-functional variants and 4 stand-alone units optimized strictly as dedicated renovation inserts. Cross-market greenfield deployment versatility is simultaneously preserved by 11 multi-functional and 6 single-function configurations, while entries engineered exclusively for new construction are completely absent across all taxonomic families.
- **Circularity Metrics (Figure A9):** Lightweight non-structural overlays thoroughly dominate the Modern Methods of Construction (MMC) classification, led by 24 multi-functional integrated and 8 single-function envelope systems (Figure A9a). Emerging circular supply chains are currently piloted via certified recycled material content (4 passive and 4 active modules), direct component reuse schemes (2 single-function systems), and reversible mechanical jointing layouts categorized under other circular aspects (Figure A9b).
- **Performance Co-Benefits (Figure A10):** Beyond operational energy savings, the R&D pipeline synthesizes multiple parallel value vectors into non-intrusive kits. Primary

energy performance improvements (triggered by 26 active multi-functional and 10 passive entries) and thermal comfort enhancements (embedded in 24 active and 10 passive prototypes) operate as a universal baseline. Indoor Environmental Quality (IEQ) optimizations are consistently registered across 18 active and 7 passive variants, while acoustic damping layers impact 10 active units. Regarding climate adaptability, 11 active systems target urban heat island mitigation, 11 optimize localized infrastructure/energy access, 9 incorporate structural fire walls, 8 deliver physical mechanical reinforcements, and 6 introduce dynamic seismic damping frames.

Usage Compatibility

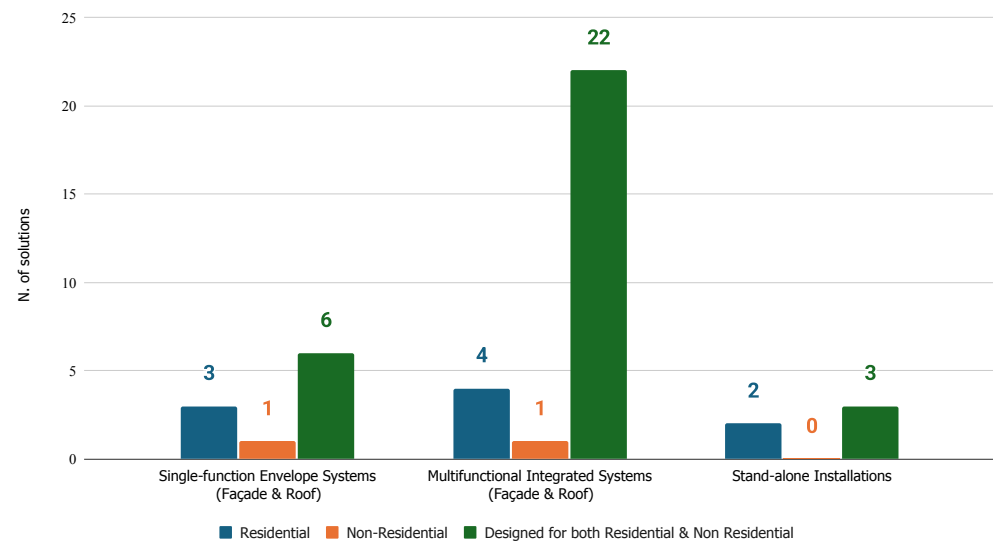


Figure A7. Usage compatibility and sector-specific applicability mapping across single-function envelope systems (Façade & Roof), multi-functional integrated systems (Façade & Roof), and stand-alone installations research prototypes (data source: BARRIO database, compiled as of March 2025).

Applicability to renovation/new construction

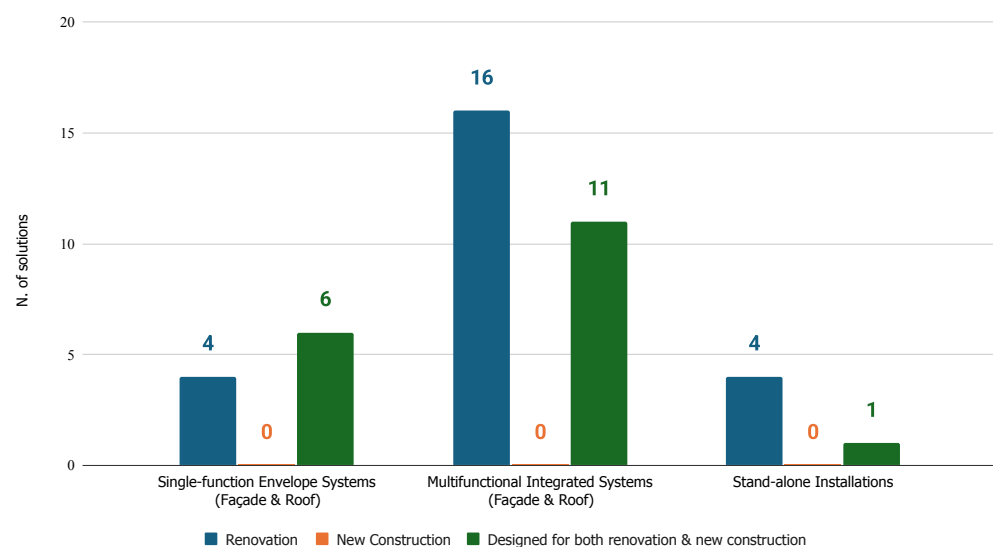
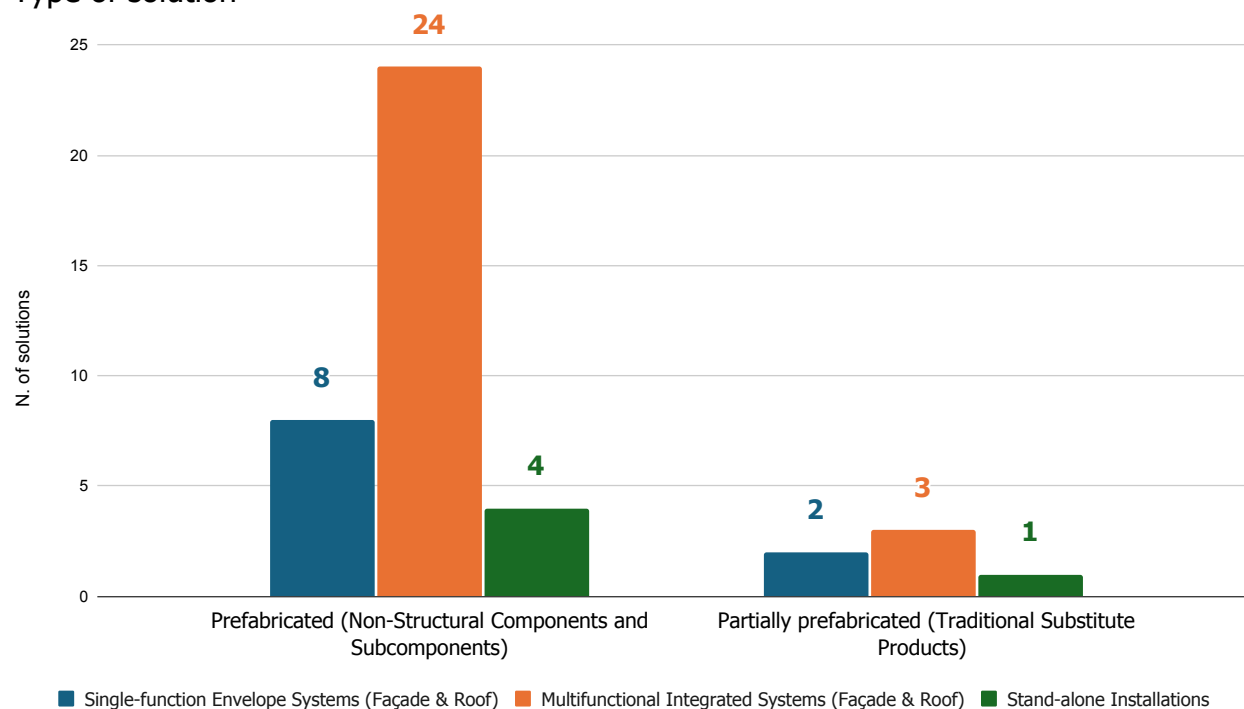


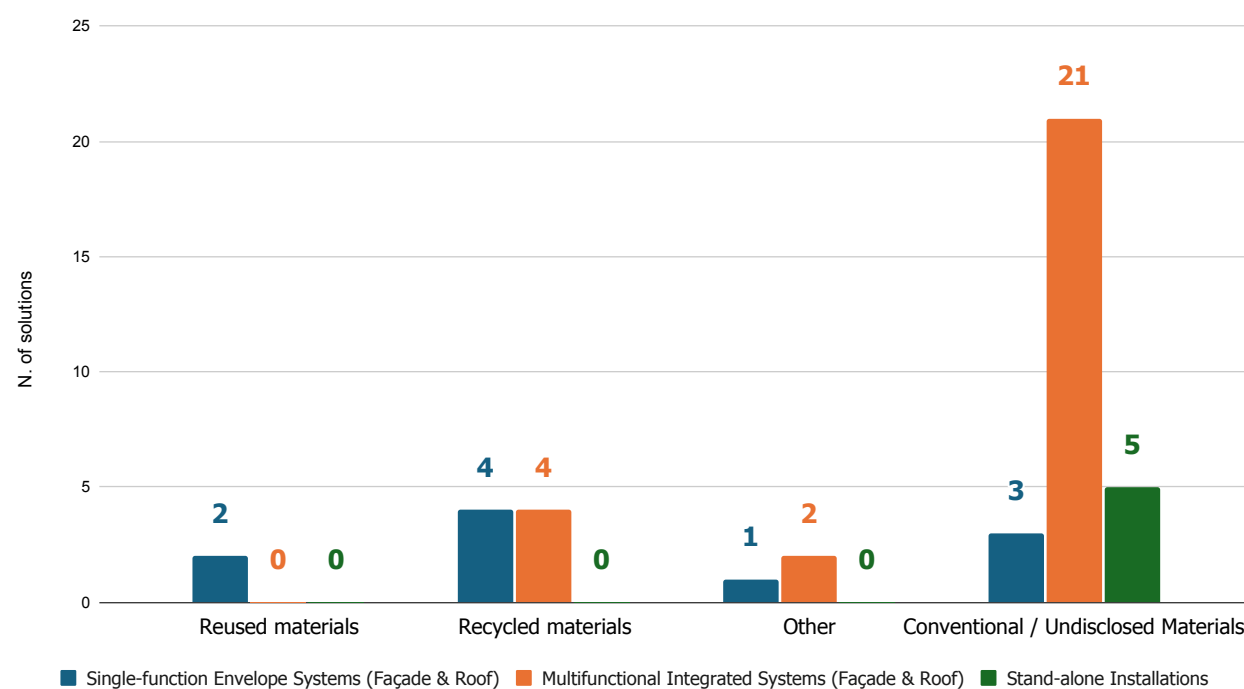
Figure A8. Operational applicability breakdown of the mapped research prototype solutions, distinguishing between dedicated renovation kits and dual-use structural systems (data source: BARRIO database, compiled as of March 2025).

Type of solution



(a)

Circularity aspects



(b)

Figure A9. Classification of research prototype solutions based on (a) Modern Methods of Construction (MMC) typologies and (b) circular economy material metrics (data source: BARRIO database, compiled as of March 2025).

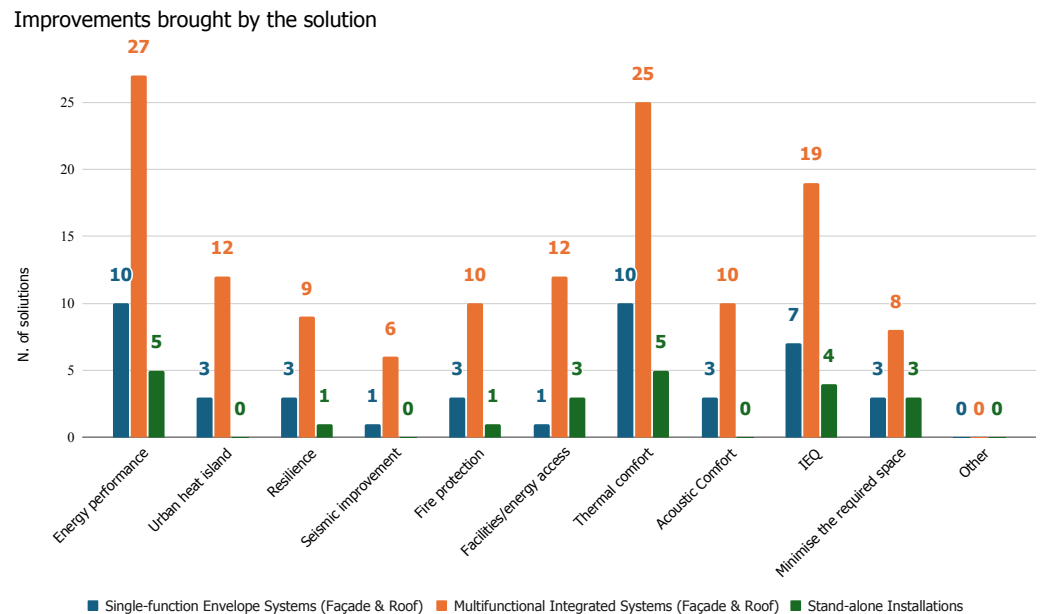


Figure A10. Systematic mapping of technical, environmental, and socio-economic performance improvements brought by the research prototype solutions (data source: BARRIO database, compiled as of March 2025).

Appendix A.3.4. Operational Vulnerabilities and Risk Code Frequency Mapping of the R&D Cohort

The quantitative tracking of internal risk codes exposes the specific technical, logistical, and administrative friction zones obstructing the research-to-market transition of the experimental kits, as mapped by the cumulative absolute frequencies in Figure A11. These counts represent the exact number of prototype configurations (out of the total R&D sub-cohort, $N = 42$) that actively trigger or require compliance with each structural, logistical, or municipal regulatory constraint:

- **BCR | Building Codes and Regulations:** This domain represents the primary administrative friction sector for experimental systems. Compliance with conflicting local structural and energy regulations (BCR1) peaks as the absolute highest threshold with 35 instances, followed closely by complex administrative permit procurement workflows (BCR2 = 28) and municipal zoning boundary restrictions (BCR3 = 8).
- **C&F | Connections and Finishing:** Post-assembly interface and handover nodes are heavily dominated by the rigorous requirements of interfacial insulation weather-proofing and atmospheric joints sealing (C&F2 = 24) and the functional execution of on-site utility network integrations (C&F1 = 22), while custom interior or exterior architectural finishing workflows (C&F3 = 3) remain a marginal concern.
- **SPF | Site Preparation and Foundation:** Substrate preparation and foundation alignment parameters impact a steady and consistent range across the prototype repository, led by geotechnical survey performance to evaluate subsurface soil bearing capacity (SPF1 = 14), pre-installation utility hookups audits (SPF4 = 9), ground grading and leveling (SPF2 = 6), and structural foundation typology matching (SPF3 = 5).
- **SR | Structural Requirements:** Mechanical host-substrate vulnerabilities constitute a fundamental barrier to scalable deployment. Guaranteeing the load-bearing capacity of the aging host framework against component dead weights (SR1) constrains 33 solutions, while designing anchoring sub-frames to absorb localized aerodynamic wind load profiles (SR2) and mandatory seismic criteria (SR3) restricts 20 and 9 prototypes, respectively.

- **T&I | Transportation and Installation:** High-density urban site logistics present intense operational friction for large-scale prefabrication, primarily driven by physical site access bottlenecks for heavy delivery vehicles (T&I1 = 26), a critical structural shortage of certified DfMA assembly labor (T&I3 = 24), and tight hoisting machinery or crane deployment parameters (T&I2 = 11).
- **Transversal Safeguards:** Cross-cutting qualitative compliance metrics show that structural fire safety standards tracking remains an active focus for 5 prototype configurations, while systemic life-cycle environmental sustainability targets and universal inclusive accessibility criteria each register 3 explicit mentions.

Requirements

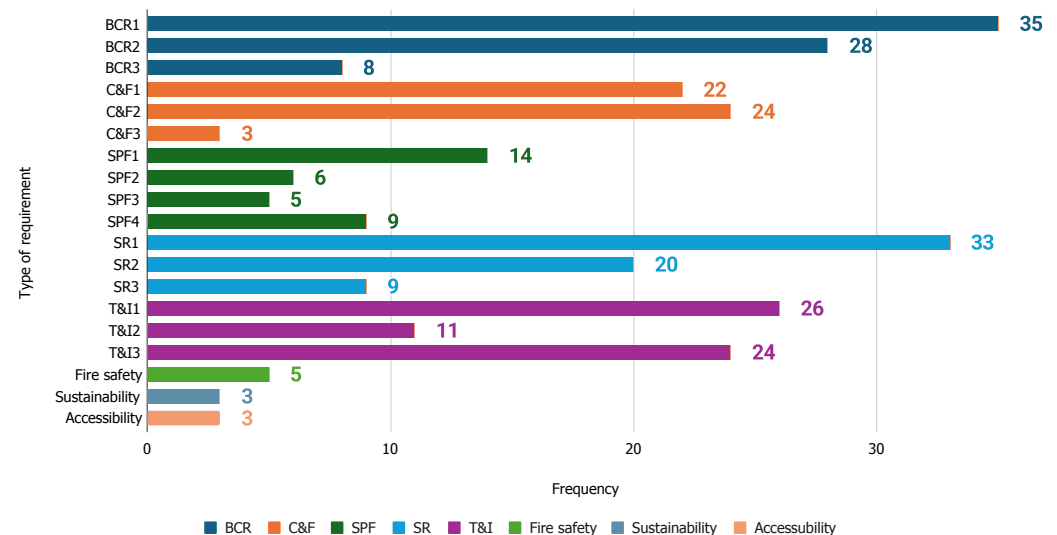


Figure A11. Quantitative frequency distribution of technical risk codes and installation requirements across the cohort of $N = 42$ research prototype technologies. (Frequencies represent the absolute count of commercial solutions actively triggering each constraint. Data source: BARRIO database, compiled as of March 2025).

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