sustainability

MDPI

Article

Wood- and Steel-Based Offsite Construction Solutions for Sustainable Building Renovation: Assessing the European and Italian Contexts

Graziano Salvalai [1,*], Francesca Gadusso [1] and Miriam Benedetti [2]

[1] Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, 20133 Milan, Italy; francesca.gadusso@polimi.it
[2] Agenzia Nazionale per le Nuove Tecnologie, l'Energia e lo Sviluppo Economico Sostenibile (ENEA), 00196 Rome, Italy; miriam.benedetti@enea.it
* Correspondence: graziano.salvalai@polimi.it

Abstract

Offsite construction (OSC) offers a promising alternative for accelerating refurbishment projects across Italy and Europe. However, its adoption remains limited due to technical, regulatory, and cultural barriers. This study, conducted as part of the OFFICIO project, maps the current European OSC landscape, with a focus on wood and light-steel technologies for sustainable building refurbishment. Combining a literature review, analysis of funded projects, and market data for 541 OSC products, the study develops tailored KPIs to assess these products' technical maturity, prefabrication level, and environmental integration. The results reveal that wood-based OSC, although less widespread, is more mature and centered on the use of multi-layer panels, while steel-based systems, though more prevalent, remain largely tied to semi-offsite construction, indicating untapped development potential. Research efforts, especially concentrated in Mediterranean regions, focus on technological integration of renewable energy systems. A significant literature gap was identified in information concerning panel-to-wall connection, critical for renovation, limiting OSC's adaptability to regeneration of existing buildings. The findings highlight the need for cross-sector collaboration, legislative clarity, and better alignment of public procurement standards with OSC characteristics. Addressing these issues is essential to bridge the gap between research prototypes and industrial adoption and accelerate the sustainable transformation of Europe's construction sector to help meet climate neutrality targets.

Keywords: offsite construction (OSC); Industrialized building systems; prefabrication; building envelope technologies; sustainable building renovation; buildings' energy efficiency

check for updates

Academic Editor: Dexter Hunt

Received: 27 June 2025
Revised: 21 July 2025
Accepted: 24 July 2025
Published: 26 July 2025

Citation: Salvalai, G.; Gadusso, F.; Benedetti, M. Wood- and Steel-Based Offsite Construction Solutions for Sustainable Building Renovation: Assessing the European and Italian Contexts. *Sustainability* **2025**, *17*, 6799. https://doi.org/10.3390/su17156799

1. Introduction

The built environment, accounting for 37% of the global GHGs, has gained the negative role of the highest-emitting sector worldwide [1]. This impact underscores its pivotal role in fighting climate change and achieving the European Green Deal's climate neutrality goal, set for 2050 [2]. Renovation was singled out as one of the key approaches for decarbonizing the sector, with the "Renovation Wave Strategy" announced in the Green Deal [3] outlining the key principles and the main intervention areas [4]. The urgency of these actions is evident given that 85% of the European building stock was constructed before 2001, and 75% is energy-inefficient according to the current standards. It is estimated that 85–95% of those buildings will still exist by 2050 [5]. To maximize the benefits, renovation must focus on deep refurbishments that lower the energy consumption by 60–90% compared to that of the original building [6]. Moreover, renovation should improve the adaptation capacity of a building, hence addressing the need for resilience to climate change. Despite ongoing efforts, the current deep renovation rate, ranging between 0.4% and 1.2% among member states, is inadequate to meet the 2050 targets. To achieve the required 3% rate [7], the sector requires forward-thinking solutions that address both design and installation challenges while fostering sector-wide innovation.

The latest European Performance Building Directive (EPBD) revision outlines industrial solutions [8], including multi-functional prefabricated elements and district-wide renovations, that provide efficient methods to decarbonize the sector [9]. Offsite construction (OSC) uses an industrialized construction approach that involves manufacturing building elements in factories, transporting them, and assembling them on site. The degree of product industrialization varies and influences the installation processes involved. This approach promotes the introduction of Industry 4.0 principles, such as digitalization and automatized manufacturing, ensuring reliability [10], minimizing the construction times [11], and limiting the final project cost [8]. OSC moves construction processes to a controlled industrialized environment, avoiding potential delays while lowering the riks to workers. It allows for reuse and disassembling of components [12], showing great potential in fostering circularity practices. OSC technologies can also integrate renewable systems and climate control technologies, allowing for a two-in-one intervention that lowers the refurbishment costs [13] while achieving higher standards with one intervention [14,15].

Despite the underlined advantages and endorsements in European legislation, OSC adoption faces significant challenges, with the absence of government regulations said to be one of the main barriers to OSC adoption [16]. A lack of a standard and proper definition of OSC hinders the widespread use of these technologies. Classification attempts have identified different levels of complexity of OSC [17], but no official categorization exists, and a cultural gap persists [18,19], extending beyond the lack of terminology consistency. The lack of knowledge on and practice and experience in the management of OSC-based construction sites discourages practitioners from choosing OSC, together with the perceived initial investment cost and lack of technological flexibility [20]. Previous research has explored the above-mentioned barriers; however, the market responses have been limited. At the European level there are different examples of innovative OSC systems that focus on the technical advancement of their solutions or address one of the barriers mentioned above. Research groups have been examining the introduction of multi-functional OSC walls containing solar harvesting systems [21], functional, innovative, and adaptable connections [22], and the energy performance of systems that integrate heat recovery units [23].

Although these areas are essential to explore to realize the technical potential of OSC, the main barriers to its use and their causes require further investigation and strategic solutions to be effectively addressed. Defining a clear user roadmap and legislative framework could aid in closing the existing gap and finally mainstreaming this technology into everyday use. An initiative worth mentioning is *Energiesprong* [24]; founded in the Netherlands, it aims at creating an ideal market context for energy renovation by fostering the development of a cross-sector network. Policymakers, practitioners, and producers work together to create a legislative and technical environment supporting the use of energy retrofit methods based on OSC. This initiative has spread to different European countries, also being applied in Italy [25], through the implementation of the *Energiesprong* method in different pilot projects. This initiative actively contributed to the creation of an efficient methodology based on OSC and to a first attempt at cross-sectorial networking. Nevertheless, additional effort needs to be directed towards the creation of a broader framework to understand and tackle specific barriers in the creation and optimization of OSC value chains, as well as in stimulating market responses.

The OFFICIO (*Ottimizzazione Filiere oFf-site per la riqualifiCazione dell'ambIente cOstruito*) project [26] and organization exists in this context. Funded by the Ministry for the Environment and Energy Safety, it aims to characterize and propose solutions to optimize the value chain of OSC technologies for energy renovation in Italy. It is a collaborative initiative led by the national agency ENEA (*Italian National Agency for New Technologies, Energy and Sustainable Economic Development*), in partnership with the Politecnico di Milano (Polimi) Departments of Architecture, the Built Environment, and Construction Engineering (DABC) and Management, Economics, and Industrial Engineering (DIG), the Università Politecnica delle Marche Department of Industrial Engineering and Mathematical Science (DIISM), and the Università di Bologna Department of Architecture (DA). This paper, developed by the ABC Department at Politecnico di Milano, investigates the current landscape of technological offsite construction (OSC) systems for building envelopes in both national and European contexts.

This study aims to identify actionable strategies to overcome barriers to the adoption of OSC through the multi-level mapping and comparative analysis of wood- and steel-based technology supply chains. This approach enables the exploration of synergies between the two sectors and provides the potential for transferring knowledge, skills, and best practices. One of the main outcomes of this study is the systematization of information across the literature, funded research, and real market data, establishing a consistent foundation of knowledge. This is supported by two practical tools, in the form of atlases, which provide existing examples that manufacturers and designers can directly reference. Section 2 presents the mapping methodology, the development of technical atlases, and the definition of ad hoc *Key Performance Indicators* (KPIs); Section 3 outlines and summarizes the results; Section 4 discusses the key findings.. The research contributes to the growing body of knowledge on OSC and supports the broader objectives of the energy transition.

2. Materials and Methods

This chapter describes the methodological framework adopted to investigate and systematize the knowledge on offsite construction (OSC) solutions, focusing on technical innovations and research directions. The approach integrated the collection, analysis, and interpretation of data from across three sources: (1) a systematic literature review, (2) analysis of publicly funded projects, and (3) a market scan of industrial solutions. Each phase generated distinct datasets, which were iteratively cross-referenced to refine the overall analysis. For instance, if a scientific paper mentioned a company, further investigation was conducted, and relevant information was incorporated into the market scan database. The resulting data were organized into structured repositories aligned with each sub-phase.

A subsequent knowledge management phase synthesized the findings from across the sources, supported by the definition of KPIs. The literature review revealed research trends and geographical distributions; the project analysis identified best practices and innovation priorities; and the market scan supported the creation of a "solution atlas" while highlighting areas for market development. The methodological framework is illustrated in Figure 1. The analysis focused on envelope systems (external walls, roofs, and volumetric modules) based on wood or light-steel technologies, classified by their primary load-bearing material.

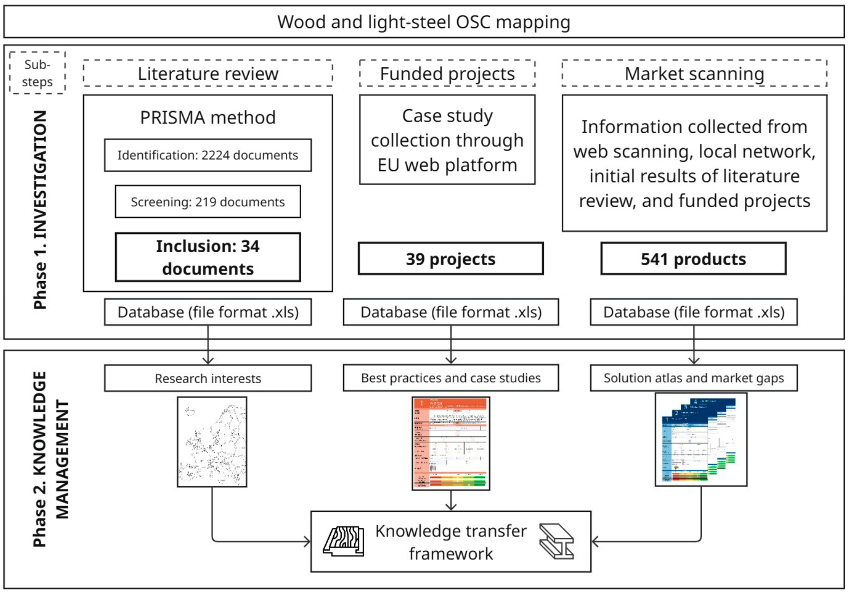


Figure 1. Methodological scheme of the research contribution of the DABC to the OFFICIO project.

2.1. Literature Review

The literature review was conducted using Scopus and Web of Science, selected for their comprehensive coverage of peer-reviewed publications. Google Scholar was not used, as its search algorithm does not allow for rigorous replication and comparison of results across databases, and its broader scope means it often retrieves non-peer-reviewed sources. The identification and screening of the sources followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology [27] to ensure transparency and reproducibility. To define the search terms, the research problem was deconstructed into four central dimensions, which informed four corresponding groups of keywords (see Figure 2): the construction method, investigated technologies, technological scope, and type of application.

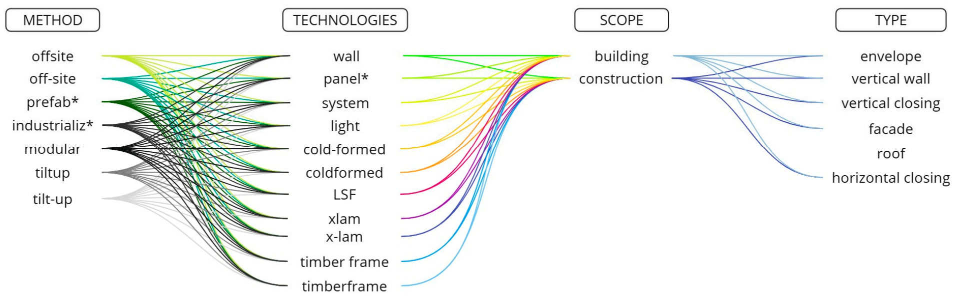


Figure 2. The four research pillars and corresponding keyword groups (*) asterisk symbol acts like a wildcard, representing zero or more characters at the end of a word. This allows to search for variations of a word with different endings. For example, prefab*, would find "prefab", "prefabrication", "prefabricated". In the final inclusion phase, two categories of publications were retained: (1) studies providing a clear technical description of OSC technologies, including their functional layers, system performance, and applications and case study demonstrations, and (2) studies presenting innovative processes or tools for building renovation and construction using prefabricated elements [28]. Only publications from the last decade (2013–2023) were considered to ensure relevant and updated findings. The selected articles were compiled into an MS Excel database and categorized according to key attributes relevant to the research scope: the core technology (wood or steel), primary application (retrofit or new construction), publication type (literature review, research project, applied research, or other), and type of innovation (renewable integration, joint systems, structural approach, or business model). A detailed scheme of the classification framework is provided in Figure 3.

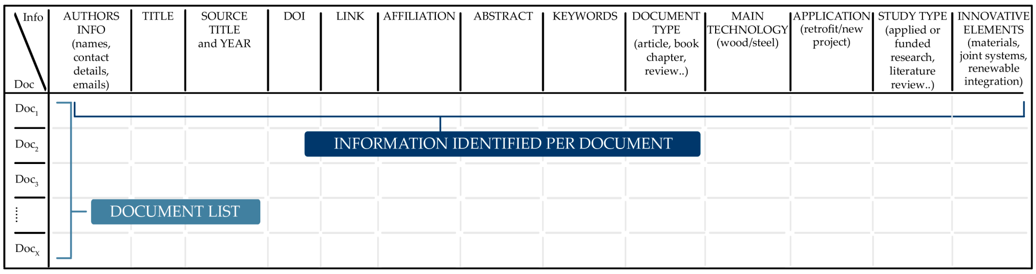


Figure 3. Schematization of the constructed literature review dataset.

2.2. Funded Research Projects

To narrow the investigation to funded projects, the European Commission CORDIS [29] database was used as the primary search platform. In line with the literature review, the selected projects focused on renovation or construction methodologies based on OSC, as well as on innovative OSC technologies. The identified projects were compiled into an MS Excel database and classified according to the following criteria: the general project description, type of technology (wood or steel), main application (retrofit or new construction), type of prefabrication (2D or 3D), level of prefabrication, and integrated systems used. A detailed schematization of the dataset is provided in Figure 4.

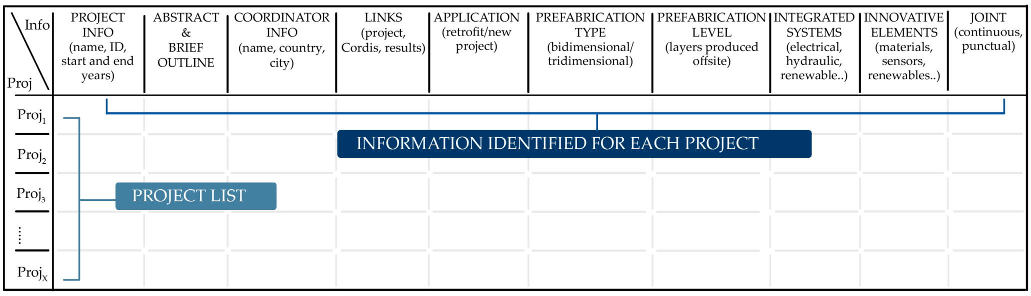


Figure 4. Schematization of the constructed funded project dataset.

Once compiled, the project data were processed automatically to generate a technical summary sheet (Figure 5).

The bottom part of the sheet shows the "performance evaluation" based on the three KPIs adopted, for which the product is rated on a discrete five-level graded scale. The calculation method for each is described and detailed in Table 1. Notably, the "product innovation" KPI assigns higher weight to the integration of sensors within the panel layers. This emphasis reflects the added value of sensor technology, which enables real-time building monitoring, facilitates predictive and targeted maintenance, reduces the downtime, and minimizes the need for interventions.

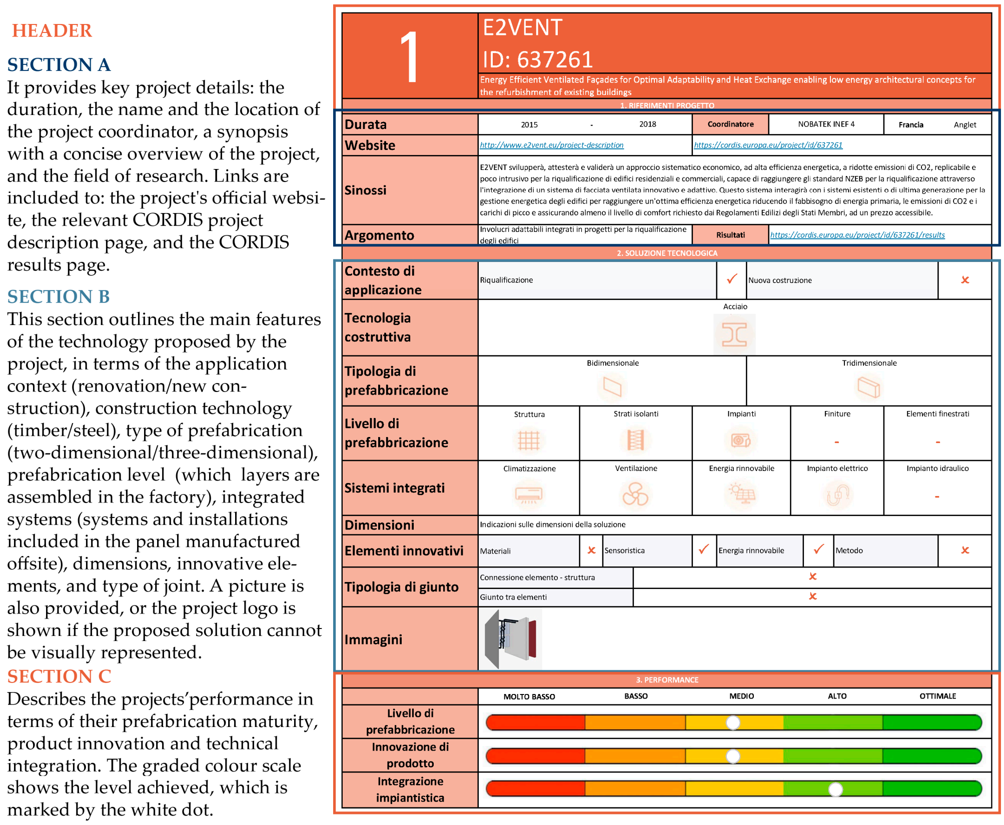


Figure 5. Visual representation of the automatically produced project datasheet.

Table 1. Calculation of projects' KPIs.

KPIs	Calculation Method
Prefabrication level	It accounts for the functional layers in the commercialized solution, with 1 point assigned for each of the following components included in the panel: insulation, load-bearing structures, technical systems (e.g., electrical systems), external cladding or coatings, and windows or doors.
Innovation level	Up to 3 points may be awarded if the project focuses on the following innovation areas: 1 point each for the use of innovative materials, renewable energy, and new research methodologies. An additional 2 points are awarded if the project integrates sensors within the panel.
Technical integration	It verifies the inclusion of specific systems within the solution. Up to 5 points may be awarded, with 1 point assigned for each of the following integrated components: an electrical system, plumbing, climatization, ventilation, and renewable energy technologies.

2.3. Market Scanning

The investigation performed on the scientific literature and funded European projects supported the identification of industrial partners and consortium members. Attending construction fairs, personal expertise, and expert consultations also contributed to the identification of OSC manufacturers. Web research validated and refined the list of OSC producers and OSC solutions (identified via OSC manufacturers' websites), which were compiled in an MS Excel database detailing 37 technical characteristics for each one (Figure 6).

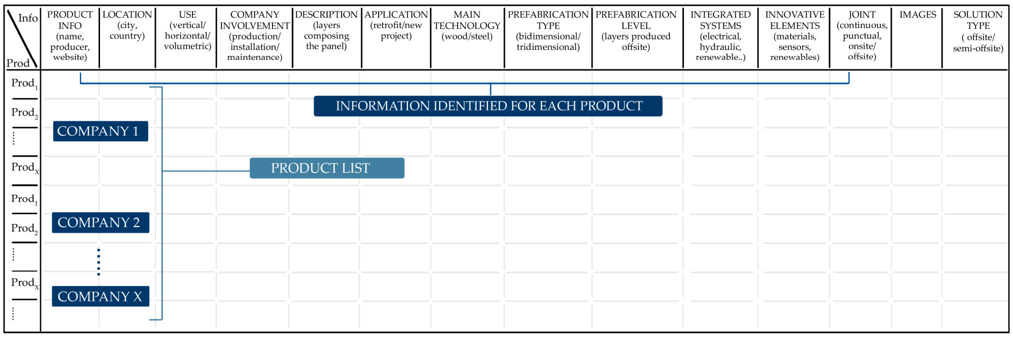


Figure 6. Schematization of the product dataset.

Upon compiling all the relevant data for the technological solutions, an automated process generated a detailed technical sheet for each product, as shown in Figure 7, outlining the key features. The technologies were classified into two main categories: semi-offsite and offsite systems. Semi-offsite solutions, such as sandwich panels, are industrialized building components that typically require additional onsite finishing or integration into a larger multi-layer wall or roof component. A practical example is a Structural Insulated Panel (SIP). SIPs are manufactured under controlled factory conditions and are composed of a foam core between two structural facings. This component is designed to be used in combination with other materials and is not suitable for independent use. In contrast, offsite systems, such as multi-layer panels and volumetric building units, exhibit a higher level of industrialization, providing plug-and-play installation, integrated insulation, and basic finishing layers. This classification served to identify technologies with the potential to evolve into comprehensive OSC retrofit systems, thereby supporting the broader objectives of this research.

The features listed in the dataset were further elaborated into four KPIs, which were included in the technical datasheets (lower part; see Figure 7). The KPIs rated the product on a discrete five-level graded scale and encompassed the prefabrication and customization levels, environmental performance, and integration of technical systems. A detailed description of the KPIs' calculation can be seen below (Table 2).

Table 2. Calculation of products' KPIs for measuring the general product's quality level.

KPIs	Calculation Method
Prefabrication level	The same as for the funded projects; see Table.
Customization level	The evaluation depends on the maturity of the solution (offsite: 1 point; semi-offsite: 0 points), the type of application (renovation or new construction: 1 point if both applications are feasible; 0 points if only one is applicable), the possibility to customize the insulation layer (1 point if customization is possible; 0 points if not), and the number of solutions offered (0 points when less than 15 products are available, 2 points if more products are provided).
Environmental performance	Points are given based on the biogenicity of the insulation layer, with a default score of 3 points if it is variable. Synthetic materials (e.g., PIR): 1 point; composite materials (e.g., phenolic foam panels): 2 points; mineral-based materials (e.g., rock wool): 3 points; vegetal materials (e.g., wood fiber): 5 points.
Technical integration	The same as for the funded projects; for reference see Table.

HEADER
Describes the projects' details, the duration, the abstract, the general topic.

SECTION A
This section provides the location of the manufacturing company (province/city and country) and includes a link to the company's website.

SECTION B
This section describes the technological solution, including the structural type, type of insulation, external cladding, and finishing layers. It then presents the main product features in terms of the application context (renovation/new construction), construction technology (timber/steel), type of prefabrication (two-dimensional/three-dimensional), level of prefabrication (which of the panel's layers are assembled in the factory), integrated systems (which systems and installations are included in the panel manufactured offsite), dimensions, innovative elements, and type of joint. An image of the solution is also provided.

SECTION C
Describes the performance level of buildings. The graded colour scale shows the level achieved, which is marked by the white dot.

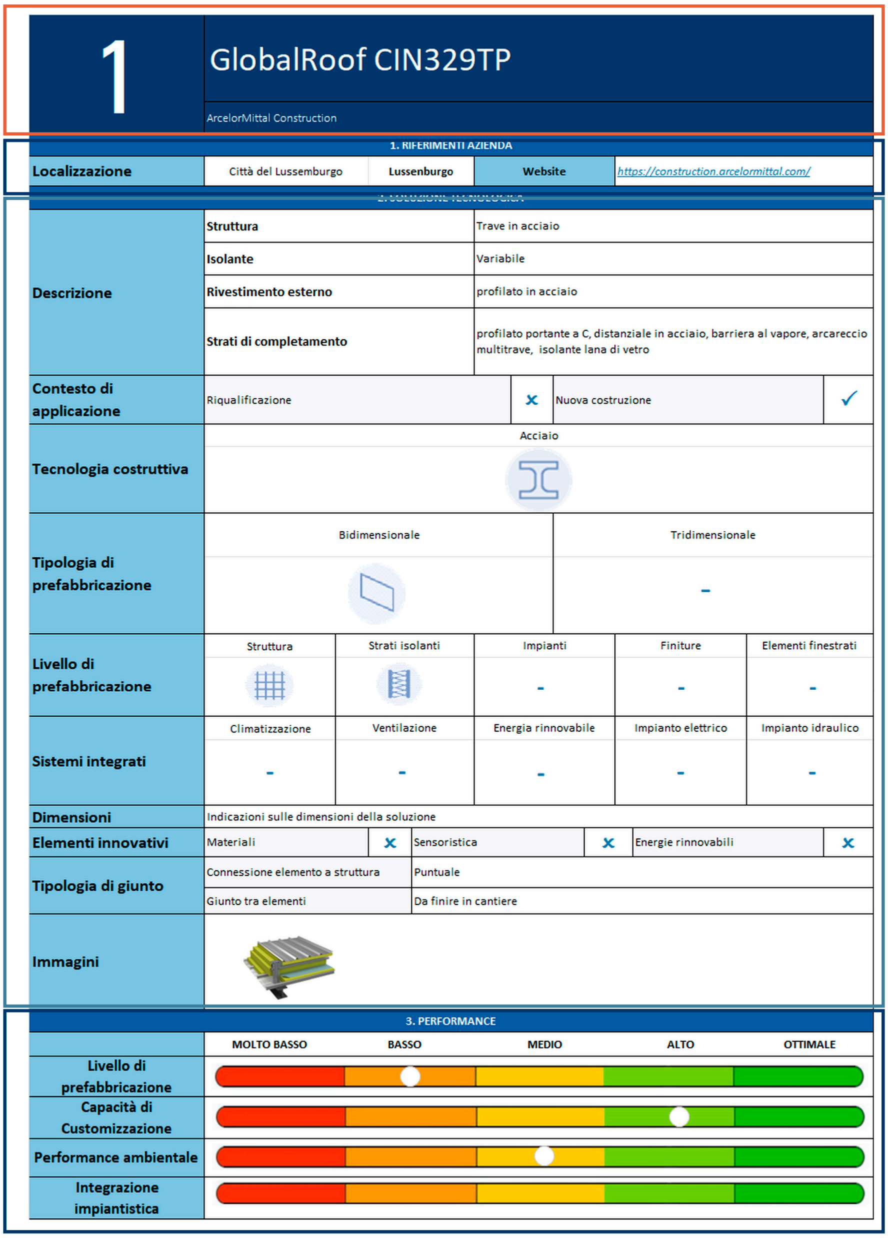


Figure 7. Visual representation of the automatically produced product datasheet.

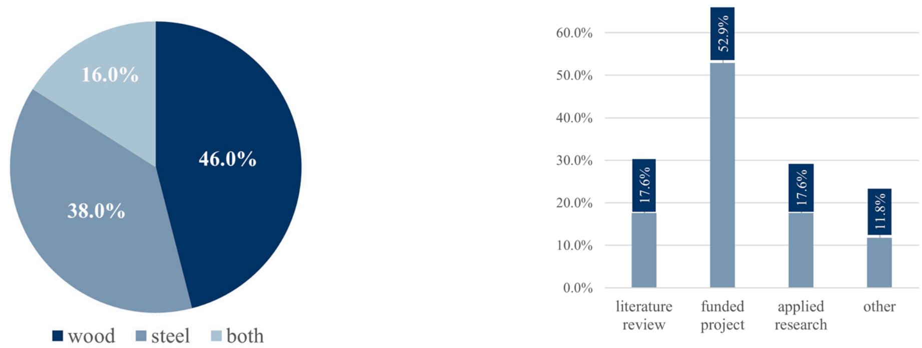
3. Results

The results are presented in three sections, corresponding to the following sections in the Methodological Section: analysis of the existing literature, analysis of funded projects, and market scanning. Each section examines key aspects of OSC technologies, enabling a comparison between academic research, funded initiatives, and commercial development. This multi-perspective approach supports a comprehensive evaluation of the current state of OSC, assessed using the defined KPIs. Additionally, the identification of development gaps and the divergences across domains informs the potential future directions for OSC. This structure provides a coherent basis for discussing the factors shaping OSC adoption and advancement, from conceptual frameworks to applied solutions.

3.1. Literature Review Results

The literature review identified a diverse range of studies, and a total of 34 documents were included and thoroughly analyzed, resulting in several key insights.

The main research interest lies in the integration of panels with specific technologies, with above 76% of the articles included focusing on this topic. Particular attention is given to the integration of renewable energy systems (RESs) within OSC technologies, covered by 35% of the articles. Of these, four articles compare different types of RES [30–33], four explore solar-related renewable integration [21,34–36], and four investigate HVAC systems or heat recovery units [23,37–39]. A minor number of articles, 17%, investigate the mechanisms of connecting OSC technologies to the existing walls. All the examined connections are dry wall connections. Almost half of the articles consider wood-based technologies (Figure 8a). Nearly 55% of the reviewed articles were funded by European Commission projects or frameworks, highlighting the significant influence of EU funding on OSC research (Figure 8b).



(**a**) (**b**)

Figure 8. (**a**) Topic distribution of wood and steel. (**b**) Distribution of article of articles.

In terms of applications, 23 articles explore retrofit solutions for existing buildings, while 8 consider applicable technologies for both retrofits and new construction projects. This distinction emphasizes the versatility and potential of OSC technologies in various construction contexts, while underlining a strong research interest in renovation in the European context.

3.2. Funded Research Project Results

Our analysis identified 39 funded projects focused on OSC technologies. There is a strong concentration of project partners in the Mediterranean area, as shown in Figure 9; Spain is involved in over 80% of the analyzed projects, followed by Italy, which is involved in 75.8% of the projects, and Germany (66.7%). These values significantly exceed the median participation rate of 12.1%, the mode of 6.1%, and the mean of 24.1%, highlighting the disproportionate concentration of research activity in a few countries. The majority of nations display markedly lower engagement, underscoring a fragmented and polarized participation landscape within the European OSC research context. This demonstrates high interest in OSC technologies in these areas while underlining the existence of a gap between necessity and market adoption and penetration.

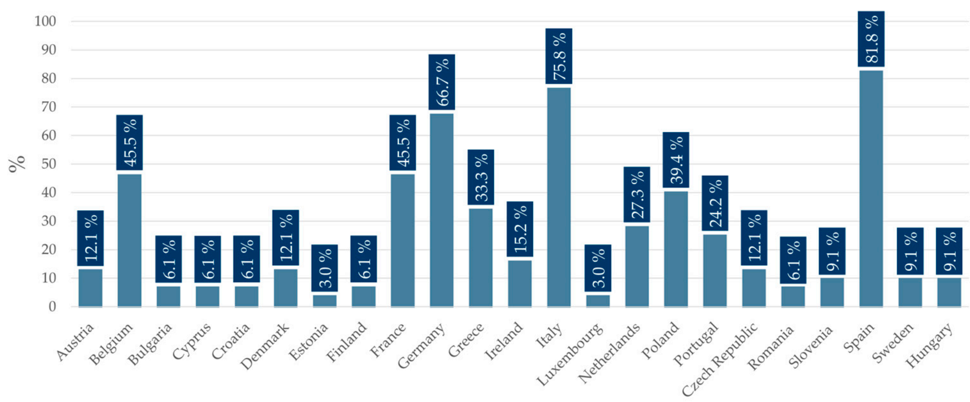


Figure 9. Geographical distribution of the project partners.

Of these projects, 27 involve steel-based technologies, while only 6 focus on wood-based systems. The remaining six projects, including three in Italy, do not concentrate on a specific OSC technology but explore methodologies or tools related to building stock renovation. These renovation methodologies often incorporate or propose the use of one or more OSC solutions. For instance, the REZBUILD [40] project is implementing a decision-making platform for deep renovation of the main European building types. Similarly, the RINNO project [41] aims to increase the renovation rates with an occupant-centered approach, proposing cost-effective solutions classified into two groups: plug-and-play modular envelopes and renewable energy storage systems. The HOUSEFUL [42] project is developing a tool to quantify the building circularity levels and redesigning traditional business models towards circularity. The CiRCUIT [43] project takes a city-wide perspective on implementing circularity, while the ABRACADABRA [44] project focuses on financing renovation strategies. The ICEBERG [45] project addresses building end-of-life issues within the context of the EU's circularity strategy. There is significant interest in integrating offsite technologies with technical systems. Nineteen projects (two wood-based, seventeen steel-based) focus on incorporating one renewable energy solution (RES) into a module. The PLURAL [46] project is attempting to integrate different types of renewable solutions, with the aim of testing them to gain an understanding of the best method for integration in a façade component. The SMAS project [47] is developing a Hybrid Natural Air Conditioning (H-NAC) system, while the ECOSANDWICH [48] project focuses on developing a ventilated wall system. Eight projects explore the use of innovative materials, including nanomaterials, vacuum-insulated panels (VIPs), and green ventilated wall infrastructure. All the projects use fully offsite technologies, while none of the projects address more complex systems (entire houses or cells) or less complex ones (semi-offsite). The analysis of the funded projects' KPIs (Figure 10) highlighted a moderate level of development across most indicators, with specific nuances tied to the scope and focus of individual project initiatives. The prefabrication level was predominantly rated as moderate, with 16 projects scoring at least 3 points, indicating the integration of multiple functional layers such as insulation, structural elements, and external cladding.

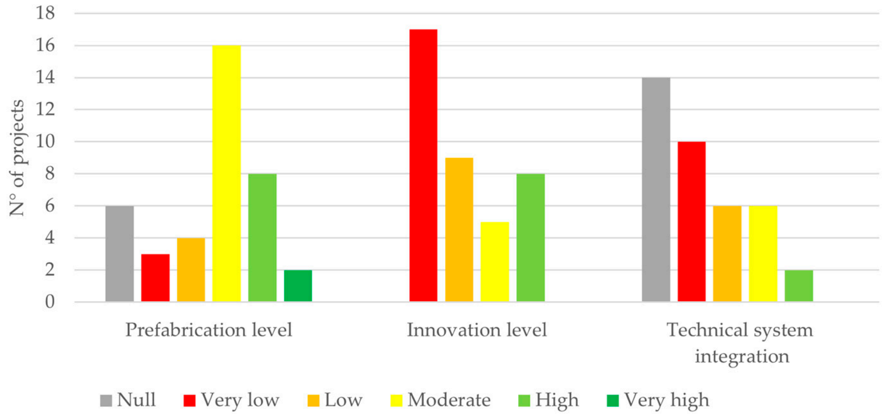


Figure 10. Analysis of the final grade distribution across the three investigated KPIs.

Notably, six projects were rated as "null" in this category, not due to a lack of prefabrication per se, but because they focused on innovative methodologies for which such an assessment was not applicable. This underscores the experimental nature of part of the research landscape. Initially, only projects focused on technology development were included; however, projects related to methodological innovation were subsequently incorporated due to their perceived relevance for this mapping exercise. Further refinements of these KPI calculations will be necessary to address this aspect more accurately. The innovation level displayed a more varied distribution: while a significant portion of the projects (17) were rated "very low", typically due to limited use of advanced materials, sensors, or renewable technologies, a considerable number (8 projects) reached "high" or "moderate" levels. This reflects a mix of conservative and progressive research strategies. Lastly, technical system integration remained limited overall, with 14 projects rated "null" and only a small subset achieving higher integration levels. This suggests that, while some projects aim for holistic offsite solutions, many still exclude technical systems from the prefabricated envelope, pointing to a critical gap in achieving full offsite integration.

3.3. Market Scanning Results

This phase of the study attempted to understand the reasons behind the barriers that prevent OSC spreading, starting with a focus on production to mirror common construction practices. We mapped 51 key players, of which 20 were Italian, accounting for the production of 541 different OSC solutions. The analysis shows the presence of three main technological families: sandwich panels, multi-layer panels, and volumetric modules. Notably, volumetric modules remain rare; only one Italian producer is included in the mapping for proposing modifications to construction site shacks for temporary residential solutions. Wood-based volumetric modules are also uncommon, with just two companies identified in Europe. A total of 83% of the analyzed OSC products are steel-based, although 42% of these are manufactured semi-offsite. Considering the division between the two macro-groups, offsite and semi-offsite, at the European level most of the mapped companies' production is fully offsite (31 companies), with 259 products manufactured fully offsite. Of these, 63% are wood-based. At the Italian level, the situation slightly shifts, and 7 out of the 13 companies producing steel-based OSC products are focusing on semi-offsite production. In fully offsite production, only 1.5% of the products are full volumetric cells. Taking into consideration the overall amount of OSC production, the Italian market seems to resemble the European one in terms of the balance between companies producing wood and steel products (Figure 11a). Most wood-based OSC manufacturers also handle product installation, while only 23% of steel-based companies provide this service. Maintenance and monitoring services are underrepresented across both material chains, indicating a critical gap in life cycle support (Figure 11c).

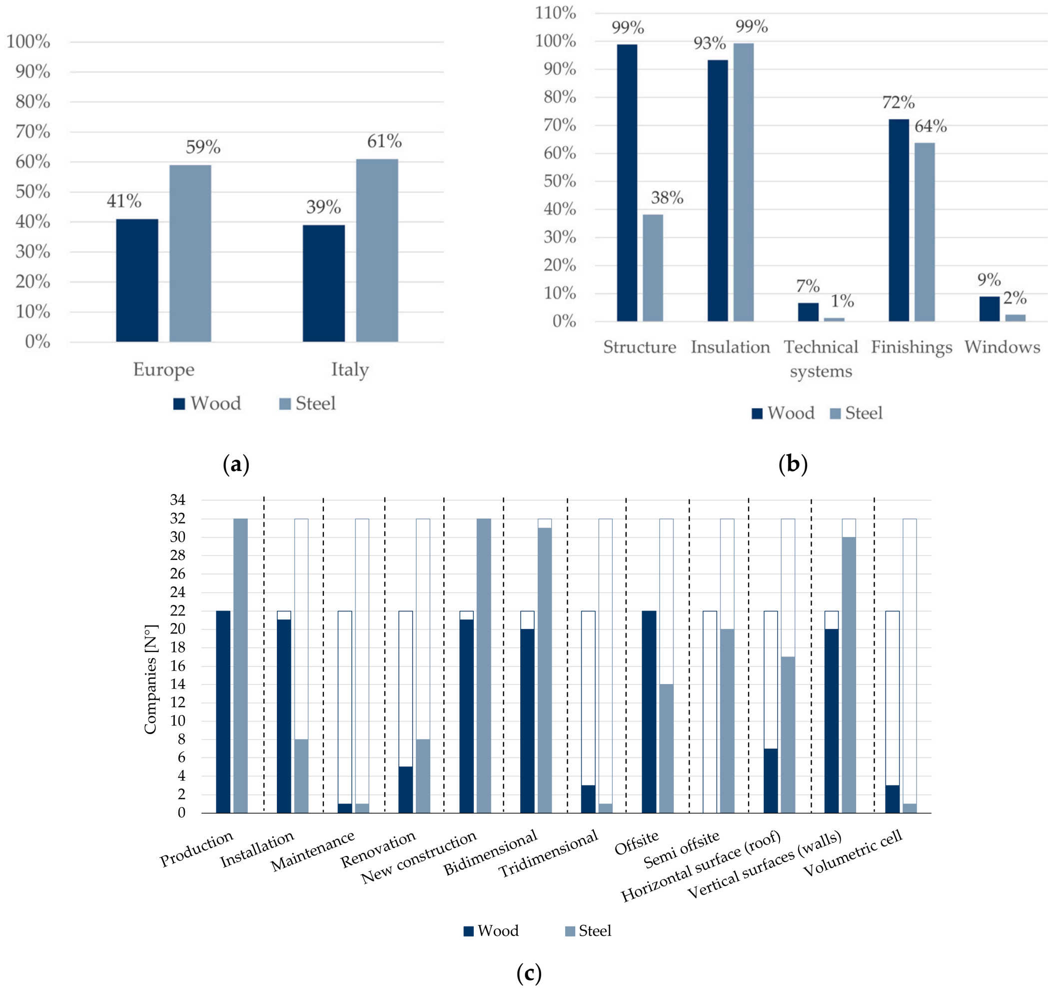


Figure 11. Analysis of overall wood and steel OSC (offsite + semi-offsite) based on data extracted from authors' database: (**a**) European vs. Italian production. (**b**). Overview of prefabrication levels in European market. (**c**) Companies producing wood and steel products: overview of analyzed characteristics.

In terms of applications, new construction overwhelmingly dominates OSC use, with renovation playing a marginal role, particularly for steel-based products. This points to a market need for adaptable solutions in retrofit scenarios. The market heavily favors bidimensional systems like panels, while volumetric modules are marginal across both material chains, likely due to logistical, cost, and standardization challenges (Figure 11c).

Regarding OSC, the wood chain exhibits a stronger commitment to fully offsite manufacturing, whereas steel companies predominantly employ semi-offsite methods, underscoring the maturity differences between the two supply chains. Vertical building elements (walls) are the primary focus for companies using both materials; however, steel companies place relatively more emphasis on horizontal surfaces such as roofs (Figure 11c).

In terms of the prefabrication level, 99% of the steel products and 93% of the wood products mapped have an insulating layer. A load-bearing structure is present in only 38% of the steel products, and this is justified by the proportion of semi-offsite production in this group (Figure 11b). Considering Figure 11, we can observe that in most of the products OSC is limited to the structural, insulating, and finishing layers and can mature more in terms of the introduction of openings and technical systems or technologies (electrical systems, climate control units, plumbing).

The KPI distribution from the market scan suggests more granularity and diversity across the performance indicators (Figure 12). Prefabrication shows a strong concentration at the "low" level (over 60%), with smaller frequencies at higher levels, reinforcing the trend of limited prefabrication maturity in the available products. The customization level demonstrates a balanced distribution between "low", "moderate", and "high", indicating that the product offerings provide varying degrees of adaptability, which may respond to different client or project needs. The environmental performance highlights a moderately encouraging picture, with the majority of systems ranked "moderate" or "very low" and a smaller proportion (around 8%) achieving "high" performance, often associated with biogenic insulation layers. In contrast, technical integration appears to be significantly underdeveloped in the market context. Over 95% of the evaluated systems score "null", suggesting that while product modularity or envelope features may be present, the integration of complete technical subsystems remains largely absent from market-ready solutions. For specific reference to the scoring system and KPI calculation, refer to Table 2.

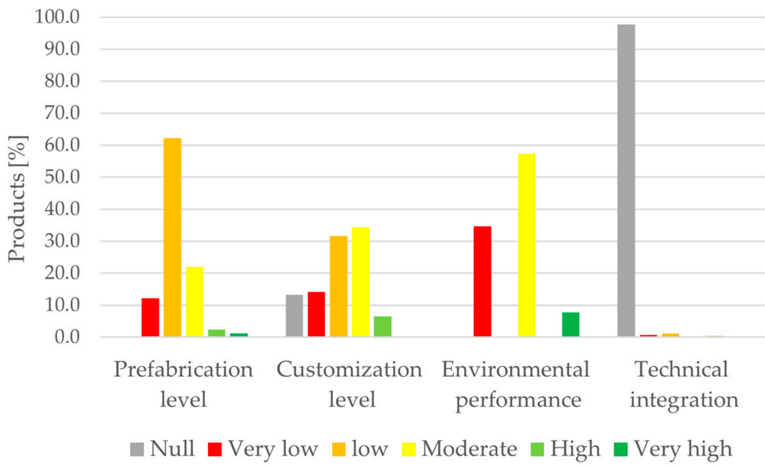


Figure 12. Analysis of the final grade distribution across the four KPIs.

4. Discussion and Conclusions

This study provides a comprehensive and multi-layered assessment of the European and Italian OSC landscape. By combining a literature review, a mapping of over 500 market products, and an in-depth evaluation of EU-funded research projects, the research sheds light on both the current limitations and underexplored potential of OSC across material systems and applications. The findings highlight a fragmented ecosystem marked by the diverging trajectories of the wood and steel supply chains, a clear misalignment between research innovation and market readiness, and critical regulatory and technical voids. While commercial offerings largely demonstrate a low prefabrication level and limited system integration, research initiatives demonstrate a more forward-looking approach, exploring higher levels of prefabrication, integration of technologies, and new models of industrial production. These dynamics reveal dual trajectories of OSC development, one driven by feasibility and incremental market evolution and the other by experimental ambition and policy-aligned innovation. At the same time, the study exposes structural barriers that limit OSC's broader adoption, particularly in renovation contexts, while also identifying promising trends that could be strategically fostered to enable sector transformation.

Among the main challenges and gaps that emerged from the analysis are the following:

- Limited system integration and industrial scalability. The market remains anchored in low-integration models: of the 541 mapped commercial OSC products, 529 exhibit no integration of technical components, such as HVAC systems or renewable energy solutions. The research projects perform slightly better, with about half showing some level of integration, yet this remains insufficient to demonstrate industrial scalability. The prefabrication levels mirror this divergence: while most market products fall in the *low* and *very low* categories, nearly 67% of EU-funded projects display *moderate* to *very high* prefabrication, indicating a research focus on more ambitious construction methodologies. However, the absence of effective knowledge transfer mechanisms prevents these research outcomes from entering the commercial pipeline.
- Inadequate applicability of OSC in current renovation practices. This study underscores the limited suitability of the current OSC solutions for energy retrofit applications. A key barrier is the lack of adaptable joint and connection systems that would allow for effective integration with existing buildings. This mapping gap, initially explored in the study but with its investigation abandoned due to a lack of public information, speaks to a broader transparency issue in the sector. Most manufacturers do not disclose technical details essential for assessing the feasibility in renovation, such as the presence of anchoring systems or modular flexibility. This limits the architectural adaptability of OSC in refurbishment, one of the most promising yet underdeveloped markets for OSC.
- Regulatory fragmentation and cultural inertia. The absence of a dedicated legislative framework [49,50], both at the national and EU levels, continues to hinder sectoral growth. Procurement standards remain misaligned with OSC characteristics, and simply adapting traditional construction norms or importing foreign standards (e.g., U.S. codes) is not feasible given Europe's heterogeneous legislative landscape. Crafting specific legal and technical instruments that recognize OSC's distinct benefits, including faster delivery, reduced onsite disruption, and enhanced safety, could dispel the prevailing misconceptions and enable broader uptake. In particular, the public sector, despite its strategic importance in leading innovation, remains constrained by traditional procurement and evaluation mechanisms that overlook the time, cost, and safety benefits of offsite systems.
- Lagging environmental assessment and traceability. Environmental performance emerged as one of the weakest areas across both the commercial and research datasets. While the market data shows increasing attention to sustainability claims, the lack of use of robust and standardized environmental metrics, such as life cycle assessments (LCAs), hampers accountability and comparability. This represents a missed opportunity, particularly considering EU decarbonization policies that prioritize circularity and emissions transparency and the explicit GHG reduction underlined in different studies [51].

Despite these significant barriers, this study also reveals encouraging trends and strategic opportunities that can be leveraged to accelerate OSC's adoption and maturity:

- Complementary evolution of material supply chains. The trajectories of wood- and steel-based OSC systems appear to be complementary rather than competitive. While wood-based solutions, representing 16% of the mapped products, are technically more advanced, typically using multi-layer panels, steel-based systems are more prevalent but remain largely in use in semi-offsite configurations. Interestingly, nearly 70% of the analyzed research projects focus on steel, indicating a targeted effort to upgrade this material stream. This convergence suggests that cross-material collaboration could yield synergies in terms of technological development, regulatory harmonization, and market expansion. Other synergies may include environmental ones, like the creation of regional shared distribution hubs and the definition of a new EPD category for OSC panels.

- Ongoing transition from semi- to fully offsite production. Several Italian firms currently producing steel solutions semi-offsite are participating in EU-funded projects aimed at achieving higher levels of prefabrication. These cross-sectoral engagements indicate an active willingness within parts of the industry to evolve toward fully offsite manufacturing. This insight highlights an opportunity to address the fragmentation of supply chains, identified by several studies as a major challenge for the sector [52]. However most current fully offsite systems remain focused on 2D rather than volumetric 3D modules, a limitation often linked to transportation and logistical constraints that should be investigated further.
- The enabling role of digital technologies. Digitalization offers transformative potential, particularly in overcoming design and implementation challenges in retrofit applications. Tools such as BIM, parametric design, and digital twin modeling can facilitate adaptive design, streamline project coordination, and enhance modular precision [52–55]. While their current use is sporadic, these technologies could serve as a bridge between the perceived rigidity and real-world complexity, improving the stakeholder confidence and expanding OSC's application spectrum.
- Movement toward circularity and sustainability. Wood-based OSC systems, due to their biogenic content, stand to benefit from a stronger alignment with EU climate policies, particularly if coupled with transparent documentation such as EPDs (Environmental Product Declarations). Although OSC's adoption is still limited, the growing policy emphasis on life cycle emissions and disassembly design could position OSC, especially the wood-based variety, as a preferred option in green public procurement and carbon-neutral development strategies.
- The creation of the OSC solution atlas. One of the most tangible outputs of this study is the development of the OSC solution atlas, a structured mapping tool comprising 541 commercial systems across Europe. By consolidating fragmented data and classifying solutions based on key technical parameters, the atlas serves as a foundational resource for bridging the information gap between researchers, designers, manufacturers, and policymakers. While the tool currently reflects the existing data limitations, it lays the groundwork for future iterations that can progressively enhance the sector's transparency and comparability, although it will need constant updates to be effective. The final version of the atlas is available on the project website [26].

In conclusion, this study demonstrates that while the European OSC sector remains fragmented and misaligned in many respects, it is also marked by active experimentation and strategic opportunities for growth. The divergence between research and market practice highlights the need for systemic mechanisms to facilitate knowledge transfer and industrial scaling of innovative solutions. To this end, the solution atlas should be seen not as a static product but as a dynamic reference to be continuously updated in response to technological advances and market evolution. The calculation of KPIs, particularly those for funded research, will need to be revised to account for the polarized results (e.g., the prefabrication level KPI). Moreover, the establishment of a cross-sector network dataset—bringing together institutions, manufacturers, researchers, and designers—is essential to ensure shared understanding, promote regulatory innovation, and foster synergies across material supply chains. Only through such integrated efforts can the full potential of OSC in contributing to the decarbonization, digitization, and industrialization of the European built environment by realized.

Author Contributions: Conceptualization, M.B. and G.S.; methodology M.B., G.S., and F.G.; data curation, F.G. and G.S.; formal analysis, F.G.; funding acquisition, M.B. and G.S.; investigation, M.B., G.S., and F.G.; project administration, M.B. and G.S.; supervision, G.S.; writing—original draft, F.G. and G.S.; writing—review and editing, M.B., G.S., and F.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Electrical System Research 2022–2024, implemented under program agreements between the Italian Ministry for Environment and Energy Security and ENEA, “Energy efficiency of industrial processes and products” project, PTR22-24_PR1.6_activity line 2.10.

Institutional Review Board Statement: Not appliable.

Informed Consent Statement: Not appliable.

Data Availability Statement: Data is contained within the article.

Acknowledgments: The author thanks the ENEA research center, the research group supporting our project, and, in particular, I. Bertini, the head of the Department of Energy Efficiency (DUEE).

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

EPD	Environmental Product Declaration
EPBD	European Performance Building Directive
GHGs	Green House Gases
HVAC	Heating Ventilation Air Conditioning
OFFICIO	Ottimizzazione Filiere oFf-site per la riqualifiCazione dell’ambIente cOstruito
OSC	Offsite Construction
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
KPIs	Key Performance Indicators
VIPs	Vacuum-Insulated Panels

References

1. United Nations Environment Programme (UNEP). Building Materials are set to dominate climate change. In *Building Materials and the Climate: Constructing a New Future*, 1st ed.; Matsny, L., Benzoni, S., Eds.; United Nations Environment Programme: Nairobi, Kenya, 2023; pp. 1–5.
2. European Commission (Brussels, Belgium). Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. In The European Green Deal; COM/2019/640 Final; 2019. Available online: https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF (accessed on 17 July 2025).
3. European Commission (Brussels, Belgium). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. In A Renovation Wave for Europe—Greening Our Buildings, Creating Jobs, Improving Lives; COM/2020/662 Final; 2020. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52020DC0662 (accessed on 17 July 2025).
4. Fetting, C. *The European Green Deal*; ESDN Report; ESDN Office: Vienna, Austria, 2020.
5. BPIE (Buildings Performance Institute Europe). EU Buildings Climate Tracker: A Call for Faster and Bolder Action. 17 July 2023. Available online: https://www.bpie.eu/publication/eu-buildings-climate-tracker-a-call-for-faster-and-bolder-action/ (accessed on 17 July 2025).
6. Sibileau, H.; Broer, R.; Dravecký, L.; Fabbri, M.; Fernández Álvarez, X.; Kockat, J.; Jankovic, I. *Deep Renovation: Shifting from Exception to Standard Practice in Eu Policy*; Buildings Performance Institute Europe (BPIE): Berlin, Germany, 2021; pp. 8–11.
7. Filippidou, F.; Navarro, J.; Filippidou, F.; Pablo, J. *Achieving the Cost-Effective Energy Transformation of Europe’s Buildings Energy Renovations via Combinations of Insulation and Heating & Cooling Technologies Methods and Data*; Publications Office of the European Union: Luxembourg, 2019; pp. 1–10.

8. European Parliament (Strasbourg, France). The European Parliament and the Council of the European Union Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024; In Energy Performance of Buildings (Recast); 2024/1275; Official Journal of the European Union. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202401275&pk_keyword=Energy&pk_content=Directive (accessed on 17 July 2025).
9. Maduta, C.; Tsemekidi-Tzeinaraki, S.; Castellazzi, L.; Dagostino, D.; Melica, G.; Paci, D.; Bertoldi, P. *Updates on the Energy Performance of Buildings Directive implementation in the EU Member States*; Publications Office of the European Union: Luxembourg, 2025.
10. Mehdipoor, A.; Iordanova, I. Systematic Literature Review on the Combination of Digital Fabrication, BIM and Off-Site Manufacturing in Construction—A Research Road Map. *Lect. Notes in Civil Eng.* **2023**, *247*, 283–296.
11. Bowden, S.; Dorr, A.; Thorpe, T.; Anumba, C. Mobile ICT Support for Construction Process Improvement. *Autom. Constr.* **2006**, *15*, 664–676. [CrossRef]
12. Bergmans, I.J.B.; Bhochhibhoya, S.; Van Oorschot, J.A.W.H. Assessing the Circular Redesign of Prefabricated Building Envelope Elements for Carbon Neutral Renovation. *J. Facade Des. Eng.* **2023**, *11*, 169–196. [CrossRef]
13. Jin Wen Thoy, E.; Go, Y.I. Enhancement and Validation of Building Integrated PV System: 3D Modelling, Techno-Economics and Environmental Assessment. *Energy Built Environ.* **2022**, *3*, 444–466. [CrossRef]
14. Zarghami, E.; Fatourehchi, D. Comparative Analysis of Rating Systems in Developing and Developed Countries: A Systematic Review and a Future Agenda towards a Region-Based Sustainability Assessment. *J. Clean Prod.* **2020**, *254*, 120024. [CrossRef]
15. Luna, A.; Gonzalez-Trevizo, M.E.; Bojorquez, G.; Romero Moreno, R.A.; Martínez-Torres, K.E. Structural Insulation Panel System (SIP) as an Alternative for Cooling Energy Saving, Decarbonization, and Energy Cost Reduction in Hot and Dry Climates. A Simulation-Based Approach. *Energy Sources Part A Recovery Util. Environ. Eff.* **2024**, *46*, 17267–17292.
16. D'Oca, S.; Ferrante, A.; Ferrer, C.; Pernetti, R.; Gralka, A.; Sebastian, R.; Veld, P. op t. Technical, Financial, and Social Barriers and Challenges in Deep Building Renovation: Integration of Lessons Learned from the H2020 Cluster Projects. *Buildings* **2018**, *8*, 174. [CrossRef]
17. Gibb, A.G.F. Standardization and Pre-Assembly- Distinguishing Myth from Reality Using Case Study Research. *Constr. Manag. Econ.* **2001**, *19*, 307–315. [CrossRef]
18. EDERA. *Materiali. Industrialized Deep Renovation Outlook*. Available online: https://edera.city/materiali/ (accessed on 17 July 2025).
19. BUILD UP. The European Portal for Energy Efficiency and Renewable Energy in Buildings. Market Potential of Offsite Construction for Housing Supply. Report. Available online: https://build-up.ec.europa.eu/en/resources-and-tools/publications/offsite-construction-key-more-affordable-housing-report (accessed on 17 July 2025).
20. Han, Y.; Wang, L. Identifying Barriers to Off-Site Construction Using Grey DEMATEL Approach: Case of China. *J. Civ. Eng. Manag.* **2018**, *24*, 364–377. [CrossRef]
21. Alvarez-Alava, I.; Elguezabal, P.; Jorge, N.; Armijos-Moya, T.; Konstantinou, T. Definition and Design of a Prefabricated and Modular Façade System to Incorporate Solar Harvesting Technologies. *J. Facade Des. Eng.* **2023**, *11*, 1–28. [CrossRef]
22. Masip, D.; Marrone, G.; Rafols Ribas, I. Implementation of a Multifunctional Plug-and-Play Façade Using a Set-Based Design Approach. *J. Facade Des. Eng.* **2023**, *11*, 71–96. [CrossRef]
23. Diallo, T.M.O.; Zhao, X.; Dugue, A.; Bonnamy, P.; Javier Miguel, F.; Martinez, A.; Theodosiou, T.; Liu, J.S.; Brown, N. Numerical Investigation of the Energy Performance of an Opaque Ventilated Façade System Employing a Smart Modular Heat Recovery Unit and a Latent Heat Thermal Energy System. *Appl Energy* **2017**, *205*, 130–152. [CrossRef]
24. Energiesprong Global Alliance. Available online: https://energiesprong.org/ (accessed on 10 June 2024).
25. Energiesprong IT Edera. Available online: https://www.energiesprong.it/il-processo/edera/ (accessed on 17 July 2024).
26. OFFICIO. Costruire il Future—Off-Site e Riqualificazione Edilizia in Italia. Available online: https://progetto-officio.it/ (accessed on 17 July 2025).
27. Page, M.; McKenzie, J.; Bossuyt, P.; Boutron, I.; Hoffmann, T.; Mulrow, C.; Shamseer, L.; Tetzlaff, J.; Akl, E.; Brennan, S.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, n71. [CrossRef]
28. Iturralde, K.; Mediavila, A.; Elguezabal, P. Automation Process in Data Collection for Representing Façades in Building Models as Part of the Renovation Process. *J. Facade Des. Eng.* **2023**, *11*, 123–144. [CrossRef]
29. European Commission CORDIS—EU Research Results. Available online: https://cordis.europa.eu/ (accessed on 6 February 2025).
30. Li, Y.; Chen, L. Investigation of European Modular Façade System Utilizing Renewable Energy. *Int. J. Low-Carbon Technol.* **2022**, *17*, 279–299. [CrossRef]
31. Favoino, F.; Perino, M.; Serra, V. Advanced Integrated Facades: Concept Evolution and New Challenges. In Proceedings of the Thermal Performance of the Exterior Envelopes of Whole Buildings, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Clearwater Beach, FL, USA, 9–12 December 2019.

32. Atsonios, I.; Katsigiannis, E.; Koklas, A.; Kolaitis, D.; Founti, M.; Mouzakis, C.; Tsoutis, C.; Adamovský, D.; Colom, J.; Philippen, D.; et al. Off-Site Prefabricated Hybrid Façade Systems a Holistic Assessment. *J. Facade Des. Eng.* **2023**, *11*, 97–122. [CrossRef]
33. Du, H.; Huang, P.; Jones, P. Modular Facade Retrofit with Renewable Energy Technologies: The Definition and Current Status in Europe. *Energy Build.* **2019**, *205*, 109543. [CrossRef]
34. Bock, M. A Building Integrated Solar Thermal Collector with Active Steel Skins. *Energy Build.* **2019**, *201*, 134–147. [CrossRef]
35. Chen, T.; Tai, K.F.; Raharjo, G.P.; Heng, C.K.; Leow, S.W. A Novel Design Approach to Prefabricated BIPV Walls for Multi-Storey Buildings. *J. Build. Eng.* **2023**, *63*, 105469. [CrossRef]
36. Favoino, F.; Goia, F.; Perino, M.; Serra, V. Experimental Analysis of the Energy Performance of an ACTive, RESponsive and Solar (ACTRESS) Façade Module. *Sol. Energy* **2016**, *133*, 226–248. [CrossRef]
37. Van Roosmalen, M.; Herrmann, A.; Kumar, A. A Review of Prefabricated Self-Sufficient Facades with Integrated Decentralised HVAC and Renewable Energy Generation and Storage. *Energy Build.* **2021**, *248*, 111107. [CrossRef]
38. Goldstein, D.J. Façade-Integrated Mechanical Systems (FIMS): A New Approach for Non-Invasive Deep Energy Retrofits. In Proceedings of the Fifth International Conference on Efficient Building Design: Material and HVAC Equipment Technologies; ASHRAE, Beirut, Lebanon, 20–21 October 2022.
39. Katsigiannis, E.; Gerogiannis, P.; Atsonios, I.; Manolitsis, A.; Founti, M. SmartWall Towards Residential NZEB with Off-Site Prefabricated Hybrid Façade Systems Using a Variety of Materials. *J. Facade Des. Eng.* **2023**, *11*, 29–50. [CrossRef]
40. Zabala Innovation-Dissemination and Communication Actions REZBUILD. Integration of New Technologies for the Retrofitting of Near Zero-Energy Buildings. Available online: https://www.zabala.eu/projects/rezbuild/ (accessed on 29 May 2025).
41. Rina S.p.a. RINNO. Potenziare l'efficienza Energetica Delle Abitazioni Europee. Available online: https://www.rina.org/it/media/CaseStudies/RINNO (accessed on 13 May 2025).
42. LEITAT Technological Center HOUSEFUL. Innovative Circular Solutions and Services for the Housing Sector. Available online: https://leitat.org/es/blog/houseful/ (accessed on 22 May 2025).
43. Circuit Consortium CIRCUIT. Circuit Construction in Regenerative Cities. Available online: https://report.circuit-project.eu/ (accessed on 22 May 2025).
44. Università di Bologna. Dipartimento di Architettura—DA ABRACADABRA. Assistant Buildings' Addition to Retrofit, Adopt, Cure and Develop the Actual Buildings up to ZeRo Energy. Available online: https://da.unibo.it/en/research/research-projects/project-archive/abracadabra (accessed on 19 May 2025).
45. Iceberg Circular Economy of Building Materials. Available online: https://iceberg-project.eu (accessed on 13 May 2025).
46. National Technical University of Athens PLURAL. Plug-and-Use Renovation with Adaptable Lightweight Systems. Available online: https://www.plural-renovation.eu/ (accessed on 19 May 2025).
47. European Commission SMAS. Sustainable Modular Architectural System. Available online: https://cordis.europa.eu/project/id/718020/reporting (accessed on 12 May 2025).
48. Eco-Sandwich Project Partners ECO-SANDWICH®—Energy Efficient, Recycled Concrete Sandwich Facade Panel. Available online: https://www.eco-sandwich.hr/ (accessed on 12 May 2025).
49. Mao, C.; Shen, Q.; Pan, W.; Ye, K. Major Barriers to Off-Site Construction: The Developer's Perspective in China. *J. Manag. Eng.* **2015**, *31*, 04014043. [CrossRef]
50. Gan, X.; Chang, R.; Zuo, J.; Wen, T.; Zillante, G. Barriers to the transition towards off-site construction in China: An Interpretivestructural modeling approach. *J. Clean. Prod.* **2018**, *197*, 8–18. [CrossRef]
51. Pervez, H.; Ali, Y.; Petrillo, A. A quantitative assessment of greenhouse gas (GHG) emissions from conventional and modular construction: A case of developing country. *J. Clean. Prod.* **2021**, *294*, 126210. [CrossRef]
52. Opabola, E.A.; Galasso, C. A probabilistic framework for post-disaster recovery modeling of buildings and electric power networks in developing countries. *Reliab. Eng. Syst. Saf.* **2024**, *242*, 109679. [CrossRef]
53. Zohourian, M.; Pamidimukkala, A.; Kermanshachi, S.; Almaskati, D. Modular Construction: A Comprehensive Review. *Buildings* **2025**, *15*, 2020. [CrossRef]
54. Wang, Y.; Bian, S.; Dong, L.; Li, H. Multiresolution Modeling of a Modular Building Design Process Based on Design Structure Matrix. *Buildings* **2023**, *13*, 2330. [CrossRef]
55. Regona, M.; Yigitcanlar, T.; Xia, B.; Li, R.Y.M. Opportunities and adoption challenges of AI in the construction industry: A PRISMA review. *J. Open Innov. Technol. Mark. Complex.* **2022**, *8*, 45. [CrossRef]