# Integrating Circular Economy Principles into Industrialized Façade Renovation Systems: A Multi-KPI Assessment

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**Abstract.** This study investigates how circular economy principles can be integrated into industrialized building envelope renovation systems to reduce environmental impacts and support the EU's climate neutrality targets. In the context of a real-world façade renovation scenario, a multi-KPI methodology is applied to assess resource efficiency and sustainability across four European demonstration buildings. The approach combines the hierarchical alignment of Key Performance Indicators (KPIs) - particularly Global Warming Potential (GWP), reuse, recycling, and biobased content—with decision-making analyses that link material choices to quantifiable environmental effects. An assembly-level assessments support transparency in design decisions and highlight the influence of stakeholder engagement, regulatory constraints, and economic considerations. Results show significant variability in GWP across façade systems, largely driven by structural materials such as steel and aluminium, while biobased insulation contributes notable carbon reductions. The comparison of the façade renovation solutions with alternative material strategies demonstrates the potential for lower-carbon renovation systems through increased use of timber structures, biobased composites, and recycled materials. The study concludes that early integration of sustainability expertise and KPI-driven design processes is essential to achieving resource-efficient, low-carbon renovation outcomes, providing a practical roadmap for advancing circularity in the built environment.

**Keywords:** circular renovation · industrialized façade systems · life cycle assessment · KPIs · Global Warming Potential · circular economy

## 1 Introduction

The Circular Economy (CE) promotes resource efficiency by narrowing, slowing, and closing material loops [1]. Standardized methods such as Life Cycle Assessment (LCA) and the Level(s) methodology [2], provide a framework for assessing carbon emissions and resource consumption in the built environment.

Achieving climate neutrality by 2050 [3] requires decarbonization, resource efficiency, and large-scale renovation. Over 85% of European buildings fail to meet energy

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efficiency standards [4]. While deep renovations can cut energy consumption by 60–90% [5], the current renovation rate is insufficient [4]. The EU Renovation Wave [4] aims to double energy-based renovations by 2030 to accelerate progress. By 2027, life-cycle Global Warming Potential (GWP) calculations will be mandatory for construction projects [6], emphasizing the need for circular renovation strategies.

A shift from traditional to industrialized renovation systems is crucial to achieving efficiency and sustainability. Prefabricated solutions enhance speed, reduce disruption, and allow for modular adaptability. This study examines circularity considerations in developing an industrialized building envelope renovation system of a real case scenario [7] (illustrated in Fig. 1).

The study adopts a multi-KPI (Key Performance Indicator) approach, structured as follows:

- Hierarchical alignment of KPIs, aligning LCA [8, 9] and Level(s) framework [2] with common CE definitions.
- Decision-making impact assessment, linking design choices to environmental KPIs such as GWP.
- Assembly-level evaluation, providing granular insights into the environmental performance of a modular system and alternative solutions.

Analyzing building systems at the assembly level is crucial, as it allows design solutions and research findings to be transferred across projects due to their scalability and applicability to diverse construction contexts. The present research aims to support sustainable renovation practices by providing transferable strategies that enable measurable environmental benefits.

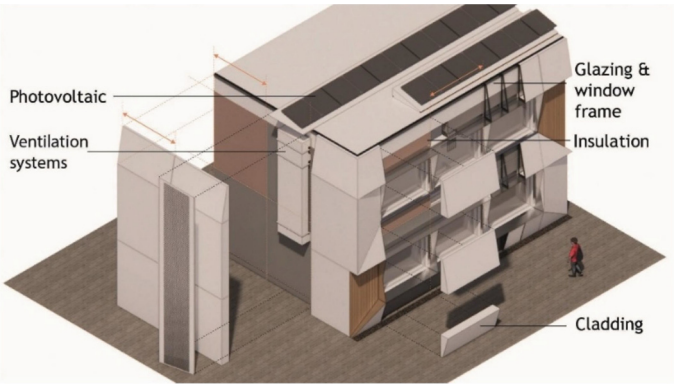



**Fig. 1** AEGIR façade system. Image courtesy of AEGIR project partner UNStudio

## 2 Methodology

The approach of the study targets the hierarchical alignment of a multiple-KPI perspective based on the following consideration:

- Identification and hierarchical alignment of KPI's (Sect. 3),
- Linking decisions to environmental effects and KPIs (Sect. 4), and
- Assessment at the Assembly-Level and proposing alternative solutions (Sect. 5).

The decision making is implemented in the renovation design and evaluation of 4 demo cases presented in Table 1.

**Table 1.** Overview of AEGIR demo buildings

| | Demo 1 | Demo 2 | Demo 3 | Demo 4 |
|---|---|---|---|---|
| Photo |  |  |  |  |
| Location | Denmark (DK) | Spain (SP) | France (FR) | Romania (RO) |
| Description | Social housing | Educational building | Residential home for elderly people | Residential building |

## 3 Identification and Hierarchical Alignment of KPI's

KPIs guide design processes toward circularity. In the AEGIR project [7] and related studies [10–12] KPIs inform decisions on material reuse, lifespan extension, and modularity, supporting sustainability. They align with the European CE strategy and the UN 2030 Agenda [13], particularly SDG 12.

CE concepts, such as Cradle-to-Cradle (C2C) [14] and the R-strategies [15], emphasize continuous material flows and biodegradability. KPIs based on these models include material purity, recyclability and the use of renewable or biobased materials. Standard tools like LCA and Level(s) quantify environmental impacts, focusing on GWP and circularity [2]. Within the study framework, GWP and the amount of secondary resources were prioritized as KPIs, with biobased materials lowering GWP and secondary materials reducing resource extraction.

## 4 Linking Decisions to Environmental Effects and KPI's

As product selection plays a critical role in determining the future reusability, resource efficiency, and environmental impact of materials and components [16–18], the prioritized KPIs guided the decision-making process.

Environmentally responsible product selection requires comprehensive data collection at both component and material levels across multiple functional categories. Therefore, during the early design stages, a material database was developed to store all relevant product information, including quantitative data on the selected KPI's.

Architects, who significantly shape material choices and construction methods, often struggle to make environmentally responsible decisions [19] due to a lack of clear guidelines and the absence of harmonized benchmarks [20]. This highlights the crucial role of

sustainability experts in guiding the decision-making process toward environmentally friendly solutions.

### 4.1 Decision-Making in the AEGIR Project

In the AEGIR project, sustainability experts shaped decisions by evaluating products' GWP (Sect. 5) and fostering stakeholder collaboration. Across all demos, outcomes reflected the complex interplay of design, sustainability, and stakeholder interests, with regulatory, social, and financial factors strongly influencing decisions. The following sections outline stakeholder roles and key factors affecting sustainability and other project decisions.

### 4.2 Stakeholder Involvement

Across all demo projects, the involvement of sustainability experts proved to be pivotal. They played a key role in conducting LCA, advising on secondary materials, and guiding strategies for material preservation. A recurring challenge, however, was ensuring that sustainability considerations were integrated early enough in the process, as well as managing the additional costs associated with circularity strategies.

The Danish demo project highlighted the importance of clear and early communication between experts and building owners. Guidance from advisory bodies at an early stage was essential, particularly in conveying circularity principles to owners. This proved critical when economic concerns initially led to the project's rejection, demonstrating that informed dialogue can shift perspectives and enable more sustainable decisions.

Similarly, the Spanish demo project underscored the value of engaged ownership combined with early involvement of sustainability experts. This collaboration helped ensure that reused materials met both environmental performance requirements and availability constraints. Despite practical challenges, proactive engagement from the owner ultimately strengthened the project outcomes.

In the Romanian project, early involvement of contractors enabled greater flexibility in integrating circular materials and adapting construction processes accordingly. Nevertheless, the lack of stakeholders representing the end-of-life (EoL) phase limited opportunities for component reuse, pointing to the need for a more comprehensive inclusion of actors across the entire building lifecycle.

### 4.3 Sustainability Decisions in the Demonstration Projects

In the Danish demo, an early material inventory enabled the identification of reusable components, supporting material recovery and embodied carbon reduction, with ceramic tiles selected based on GWP and structural feasibility. The Spanish demo emphasized reclaimed eucalyptus wood for cladding to enhance durability and reduce carbon emissions, while also assessing laminated biobased panels for their GWP performance. In the French demo, low-carbon concrete was initially considered but ultimately replaced by aluminium cladding due to regulatory and weight constraints. In the Romanian demo, the owner's preference for virgin materials limited circular strategies, shifting the focus toward energy efficiency and influencing thermal performance decisions.

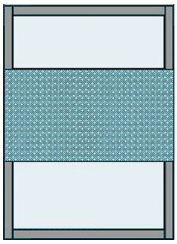
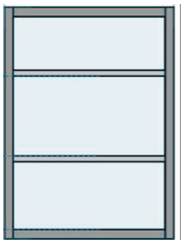
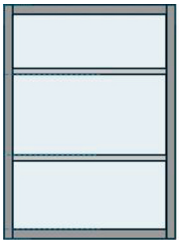
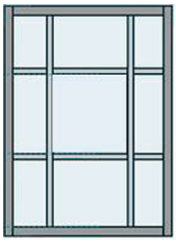
### 4.4 Other Influencing Factors

The French project illustrated how innovation is often constrained by timelines and approval processes. Lengthy regulatory procedures and concerns regarding material performance ultimately led to a shift from low-carbon concrete to conventional aluminum cladding. More broadly, decision making throughout the project was strongly shaped by regulatory and practical constraints, including weight limitations, structural requirements, fire regulations and approval timelines. In addition, cost considerations played a decisive role, with economic factors significantly influencing the final selection of materials.

## 5 Assessment at the Assembly Level

This study assesses the GWP (kg $CO_2$ eq.) of opaque façade modules used in the AEGIR demonstration projects. The system consists of modular units incorporating structural elements, internal and external enclosures, gaskets for airtightness, and insulation and cladding for thermal performance. The results are presented in Table 2.

**Table 2** Assessment of the GWP ($CO_2$ eq.) of each AEGIR opaque panel

| | Demo 1 (DK) | Demo 2 (SP) | Demo 3 (FR) | Demo 4 (RO) |
|---|---|---|---|---|
| |  |  |  |  |
| Total Area | 6.23 $m^2$ | 9.03 $m^2$ | 6.408 $m^2$ | 4.72 $m^2$ |
| Technology | PV panels | / | / | 2 Vents |
| Structure GWP | Aluminum 89.1 | Steel 17.9 | Wood -14.2 | Steel 113.4 |
| Anchorage GWP | Steel 0.2 | Steel 0.1 | Steel 0.3 | Steel 9.7 |
| Cladding GWP | Ceramic tiles 7.3 | Ceramic tiles 1.5 | Aluminum 51.5 | Ceramic tiles 7.3 |
| Insulation GWP | Woodfibre -8.4 | Woodfibre -7.9 | Woodfibre 7.7 | Woodfibre -10.8 |
| Enclosure GWP | Fiber cement 9.8 | Fiber cement 9.8 | Fiber cement 4.9 | Fiber cement 9.8 |
| PV panel GWP | 28.5 | / | / | / |

(*continued*)

**Table 2** (*continued*)

| | Demo 1 (DK) | Demo 2 (SP) | Demo 3 (FR) | Demo 4 (RO) |
|---|---|---|---|---|
| **Total GWP/m$^2$** | **96.4** | **36.3** | **38** | **155.4** |

The environmental performance of the façade systems varies considerably across the demo sites. The Danish system shows a GWP of 96.4, largely driven by the aluminium structure, which accounts for 62% of the total, while wood fibre insulation offsets emissions by 6%.

The Spanish system achieves a substantially lower GWP, supported by biogenic materials. Wood fibre insulation provides a reduction of 15%, while the steel key frame contributes to a total of 35% GWP.

The Romanian system records the highest GWP at 155.4, dominated by its steel structure, which accounts for 66% (113.4 GWP).

The French solution achieves the second-lowest GWP at 38, largely due to timber structures, which provide a reduction of 27%. However, windows and metal shading systems significantly increase the overall impact, accounting for 57% of the total GWP.

### 5.1 Development of Alternative Solutions

The AEGIR solution relies on steel and aluminium for structural components. While durable and recyclable, these materials have a high GWP due to energy-intensive production. Lower-carbon alternatives include Cross-Laminated Timber (CLT) or recycled steel and aluminium. For cladding, AEGIR uses ceramic tiles, aluminium sheets, or laminated biobased panels, which range from moderate to high GWP. Alternatives such as timber cladding, bio-based composites with improved EoL systems, or low-carbon concrete could significantly reduce emissions if recycling challenges are addressed. Biobased insulation materials like wood fibre or cellulose help offset emissions through carbon sequestration but require careful consideration of fire safety and EoL strategies. Alternatives include hempcrete or straw as biodegradable options, or recycled PET and fabric insulation, although these represent downcycling; upcycling should be prioritized.

Metal shading systems substantially increase GWP. Lower-impact alternatives include smart windows or fabric shading systems with better recyclability.

Finally, photovoltaic panels help offset embodied emissions over time, while metal-based ventilation systems contribute to GWP but are not included in the calculations. Thin-film photovoltaics, bio-based ventilation components, or manual ventilation systems could further reduce the overall environmental impact.

## 6 Conclusions

This study shows that industrialized building envelope renovation systems can significantly reduce environmental impacts when circular economy principles are embedded in early design decisions. Using a multi-KPI framework aligned with LCA and the Level(s) methodology, GWP and secondary resource use proved effective in guiding material selection toward circular solutions.

Results from the four AEGIR demonstration projects highlight that environmental performance is strongly influenced by structural systems, material choices, and stakeholder involvement. Biogenic materials consistently lowered GWP through carbon sequestration, while steel and aluminium structures dominated embodied emissions. Early involvement of sustainability experts supported informed decision-making, whereas regulatory constraints, costs, and limited end-of-life stakeholder integration often restricted circular options.

Assembly-level assessments revealed that structures, windows, and shading systems are key GWP drivers. The analysis of alternative solutions indicates further reduction potential through timber-based or recycled materials, improved EoL strategies, and lower-impact façade and energy systems.

Overall, the findings confirm that KPI-driven, industrialized renovation approaches can deliver measurable environmental benefits and support upcoming mandatory life-cycle assessments, while highlighting the need to address regulatory and process barriers to scale circular renovation practices.

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