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# Timber-Based Prefabricated Systems for Deep Renovation: A Circular Economy Perspective on Case Studies and Insights for the Australian Context

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**ABSTRACT:** Prefabricated timber façade systems have emerged as a promising solution for accelerating deep renovations, effectively addressing global targets for energy conservation and emissions reduction. These systems align closely with circular economy principles by incorporating strategies such as design for disassembly, component reuse, and modular standardization, significantly enhancing resource efficiency and reducing environmental impacts. This paper analyses eight recent European demonstration projects employing prefabricated timber façade retrofits, highlighting their design considerations, technical implementations, and associated environmental, economic, and social advantages. Insights from these cases reveal substantial opportunities for adoption within Australia's residential building stock, given structural compatibility, rapid installation, minimal occupant disruption, and integrated performance upgrades.

**KEYWORDS:** prefabricated timber façade, circular economy, deep renovation, residential retrofits

## 1 – INTRODUCTION

The building and construction sector is one of the most significant contributors to global energy consumption and $CO_2$ emissions, accounting for 34% of global energy use and 37% of $CO_2$ emissions as of 2021 [1]. Reducing the building-related share is critical to achieving the energy conservation and emission reduction targets set by nations under the Paris Agreement. A significant portion of the existing building stock was constructed before the implementation of modern energy performance regulations. Considering that demolition and rebuilding are neither economically viable nor environmentally sustainable options, these buildings are expected to remain in use for the foreseeable future. Thus, undertaking energy upgrades stands as the most effective solution to upgrade and align their energy performance to current targets. For instance, research in Europe indicates that energy demand in buildings can be reduced by up to 70% through improved insulation alone, but the sheer scale of inefficient building stock necessitates an annual renovation rate exceeding 2% to meet established energy targets [2].

While the benefits of building renovation are significant, the process may also entail hidden costs. Case studies indicate that, when viewed from a building lifecycle perspective, the waste at end-of-life can exceed the materials used during construction by as much as 40%, due to the replacement of materials and components during the building's life [3], showing that considerably amount of material and energy is underutilized during renovation. Thus, considering the significant volume of imminent building renovation activities, designing efficient renovation solutions that integrate reuse and recyclability objectives during and after a building's life can have a great impact environmentally, economically, and socially. This perspective aligns closely with the foundational principles of the circular economy, which emphasize optimizing resource efficiency and minimizing waste [4]. Since its introduction, this model has been widely studied in the building and construction sector, raising awareness of its potential to deliver significant benefits [5], [6].

The circular economy is fundamentally a guiding framework. In the context of building and construction, its application strategies can vary according to different stages of the building lifecycle, targeted objectives, and various dimensions of implementation [7]. Currently, there is a lack of standardized and universally applicable approaches, highlighting the need for case-specific strategies that balance theoretical principles with practical

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constraints [8], [9]. Despite these varied interpretations, a consensus emerges on the foundational logic of the circular economy model—namely, the imperative to narrow, slow, close, and regenerate the flows of materials and energy [10].

Within this context, timber emerges as a material of promise due to its inherent alignment with circular principles. As a renewable resource with carbon sequestration capabilities, wood offers a favourable balance of structural performance and environmental benefits. Lifecycle analyses demonstrate that timber construction can reduce embodied carbon greatly compared to steel or concrete equivalents while enabling easier material recovery at end-of-life stages [11]. Moreover, its biological composition allows multiple life cycles through cascading use models—from primary structural elements to secondary products, and ultimately to energy recovery [12]. These characteristics make timber an ideal candidate for circular construction systems.

Integrating prefabrication technology further amplifies these advantages. Prefabrication aligns with the principles of the circular economy by enhancing resource efficiency, minimizing waste, and facilitating the reuse and recycling of materials through controlled off-site production and optimized construction processes. A case shows that, for a two-storey office building, prefabricated timber components with a well-managed BIM model can achieve up to 65% in reusability rate, which can be further improved with the use of demountable connections [13]. Another research report shows up to 40% reduction in construction waste and 34% in embodied carbon for a prefabricated timber system compared with traditional methods of construction [14]. Moreover, prefabrication techniques shorten construction durations, reduce on-site errors through controlled manufacturing environments, and ensure consistent quality across components. These improvements expedite the building retrofit process, thereby enhancing the feasibility of large-scale renovations and underscoring the practical significance of relevant studies.

Over the last decade, the renovation of existing buildings using prefabricated timber components has gained momentum worldwide, driven by urgent sustainability goals, rising energy costs, and mounting pressure to minimize construction-related disruptions [15]. A substantial body of research and demonstration projects has emerged in Europe, where government-backed initiatives have advanced both technical development and market acceptance [16], [17], [18].

In Australia, the need for and context of circular deep renovation, as well as the associated challenges, closely mirror those in Europe. These challenges include a large building stock urgently requiring energy upgrades, policy mandates for emissions reduction and energy efficiency, limited clarity around behavioural motivations and outcomes, low public awareness, and higher upfront costs compared to conventional renovation methods, leading to limited uptake [19]. Moreover, Australia faces unique barriers, such as more complex housing ownership structures, a highly speculative and privatized housing market, lower energy standards than Europe, less supportive policy frameworks, and a pronounced lack of research and practical examples in this area [19]. Under these conditions, localized research is both urgent and essential. As numerous studies have been undertaken worldwide, drawing upon their lessons could be highly beneficial. Furthermore, given the practical nature of this topic, collecting insights from actual built projects, rather than purely theoretical research, would yield more substantial contributions. Based on the above discussion, the research questions of this paper are as follows:

RQ1: How do the design considerations employed in the case study align with circular design principles?

RQ2: What lessons and insights can these real-world cases provide for the Australian local building stock?

## 2 – METHODOLOGY

The methodology comprised three main steps: establishing case selection criteria, conducting literature and project searches, and systematically collecting data from suitable cases.

### 2.1 Case Selection Criteria

To ensure that the examined projects could provide meaningful insights, this study applied the following criteria:

Real-world application: The projects must involve actual, physical renovations on existing buildings rather than conceptual proposals, prototype tests, or purely academic simulations, and they require a comprehensive update of the entire building rather than only partial modifications.

Demo case selection: In instances where multiple demo cases exist within the same project, only one was selected to maintain overall diversity within the limited sample.

Documentation: Only cases with publicly accessible, detailed, and comprehensive documentation in English, such as project reports, technical specifications, or stakeholder interviews, were included. This requirement ensured the availability of both technical and contextual information for discussion.

Year: Only projects with demo cases initiated within the last decade (i.e., from 2014 onward) were considered.

Technique: The renovation had to feature timber-based, off-site fabricated façade products as a primary intervention.

### 2.2 Literature and Database Searches

The study employed a two-stage search strategy for a comprehensive result.

An academic literature search was performed in the Scopus database, using a search string '("timber" OR "wood*" OR "Bio-based") AND ("Renovat*" OR "Retrofit*") AND ("envelope" OR "facade")'. Titles and abstracts were screened for relevance, and shortlisted documents underwent full-text review to confirm that they described actual renovation projects.

In parallel, internet-based and official project database searches complemented the academic review. Publicly available repositories, such as CORDIS (an EU project database), provided detailed reports from EU-funded demonstration projects, while general online sources (e.g., official project websites, and government portals) revealed valuable case studies, often with visual documentation and stakeholder comments. Each potential project located through these channels was assessed against the selection criteria stated above.

The search led to the identification of seven relevant case studies, all located in Europe, primarily due to the region's strong policy directives, such as the Energy Performance of Buildings Directive (EPBD), which have fostered innovative renovation practices. Among them, most received funding from the European Union, necessitating comprehensive documentation and open access to project reports. The cases are as follows:

1 – INFINITE Italy case study 2 – e-SAFE real pilot building; 3 – Drive 0 Estonia demo case; 4 – PLURAL Czech demonstration; 5 – AdeSA system case study building; 6 – 4RinEU Norwegian demo case; 7 – P2Endure Warsaw demo case; 8 – MORE-CONNECT Estonia case study.

Fig. 1 presents photos from the renovation process of each case; however, as no photographs were available for Case 2, a rendered image was used as a substitute.


*Figure 1. Photo of selected cases during the renovation process*

### 2.3 Data Collection

From the final pool of identified cases, a structured data collection protocol was followed to gather consistent and comparable information across projects. The core data fields included:

a. Building Profile: Year of construction, location, height, size, structure types (ST1 – Clay brickwork/ blockwork; ST2 – Concrete brickwork/ blockwork; ST3 – Concrete beam-column structure; ST4 – Prefabricated concrete panel system; ST5 – Timber truss structure). Baseline data, such as pre-renovation energy use and façade condition, were also recorded.
b. System Profile: Details of the prefabricated timber façade system applied, including integrated sub-system type (IST1 – Building integrated photovoltaic or/and building integrated solar thermal; IST2 – Mechanical ventilation devices; IST 3 – Supply media, e.g. electric wire, water pipe; IST 4 – Heat pump; IST 5 – Smart window, only showed in case 1, configured as insulated glazing units with integrated wireless sensors for dynamic sunblind control and incorporate dual-band electrochromic glass for selective modulation of near-infrared radiation), panel sizes, load transferring mode, stratification, thermal performance, etc.
c. Key Performance Indicators (KPIs): Energy consumption and carbon footprint data before and after installation, cost, working hours, any improvements in indoor environmental quality, and metrics on waste generation or recycling.
d. Renovation Process Record: Project documentation outlining on-site installation procedures, scheduling, logistics, and financial records. Where available, construction logs and stakeholder communication notes were reviewed to capture project management details.
e. Stakeholder Perspectives: Subjective assessments from building occupants, architects, contractors, and other parties involved. This included surveys, interviews, or informal feedback on construction disruptions, perceived benefits, and lessons learned.

Both quantitative and qualitative aspects of each renovation project were captured. By examining the interplay between technical choices, project execution, and resulting performance outcomes, the study sought to derive broader insights into how prefabricated timber façade solutions can contribute to more circular renovation practices.

## 3 – PROJECT DESCRIPTION

To facilitate a preliminary understanding of the projects and their associated data, key metrics related to building characteristics, renovation systems, and common performance indicators (sourced from data categories a, b, and c in Section 2.3) were extracted and compiled into Tab. 1. It should be noted that Case 1, as the most recent pilot, has many pieces of information that have not yet


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*Table 1: Information summary for selected cases*

| | Case Number | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|
| a. Pilot Profile | Built year | | 1979 | 1964 | 1986 | 1962 | 1960 | 1970s | 1983 | 1986 |
| | Country | | Italy | Italy | Estonia | Czech | Italy | Norway | Poland | Estonia |
| | Floors above ground | | 3 | 5 | 3 | 2 | 2 | 2 | 2 | 5 |
| | Covered area (m²) | | ~200* | 301 | 864 | 196 | 131 | 215 | 631 | 737 |
| | Façade structure Type | ST1 | ● | | | ● | ● | | | |
| | | ST2 | | | | | | ● | ● | |
| | | ST3 | ● | ● | | | | | | |
| | | ST4 | | | ● | | | | ● | ● |
| | | ST5 | | | | | | ● | | |
| | HVAC energy demand (kWh/m²y) | | Un-known | 75.9 | 98 | 163 | 206 | 125.7 | 137.3 | 168 |
| b. System Profile | Project name | | INFINITE | e-SAFE | Drive 0 | PLURAL | AdeSA | 4RinEU | P2Endure | MORE-CONNECT |
| | Intergrated Sub-system type | IST1 | ● | | | | | ● | | |
| | | IST2 | ● | | ● | ● | | ● | ● | ● |
| | | IST3 | | ● | | | ● | | ● | |
| | | IST4 | | ● | | ● | | | | |
| | | IST5 | ● | | | | | | | |
| | Common panels size (mm) | | Un-known | Un-known | 5982 x2800 | 8620 x3000 | 7900 x2500 | ~3030 x6900 * | ~3600 x4400 * | 9969 x2670 |
| | Load transferring mode | | An-chored | An-chored | An-chored | An-chored | New foun-dation | New foun-dation | An-chored | An-chored |
| c. KPIs | HVAC energy reduction | | Un-known | 59% | 65% | 91% | 72% | 78% | 40% | 86% |
| | Cost Comparison | | -0.3% | Un-known | +80% | Un-known | Un-known | +58% | Un-known | +157% |
| | Installation time | | Un-known | Un-known | 10 weeks | 9 weeks | 1 week | 7 weeks | Un-known | 6 weeks |
| | Reference | | [20] to [22] | [17],[23] to [26] | [27] to [29] | [30] to [33] | [34] to [36] | [37] to [39] | [40] to [45] | [46] to [49] |

●: Included *: Inferred from reference

been disclosed or published. In addition, Case 2 employs two distinct panel types (e-CLT and e-PANEL) in its renovation; for the sake of clarity, the analysis focuses on the more extensively used e-CLT panels. Due to variations in statistical methods, scope, and timeframes, objective comparisons between projects remain challenging. Consequently, Table 1 primarily serves as an overall summary of each case.

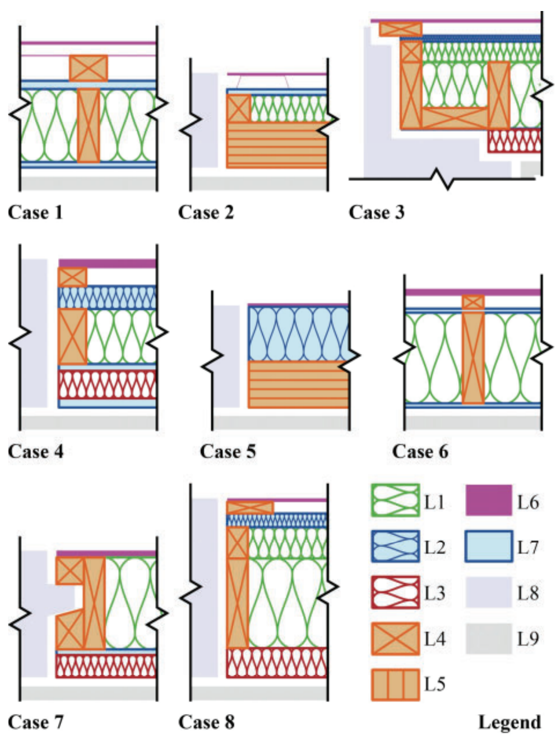
Detailed explanations for specific parameters, which acknowledge differences in statistical analysis and interpretation, are provided below:

HVAC energy data: Case 2, simulated by Energyplus; Case 3, measured Energy Performance Value; Case 4, simulated by TRYNSYS- Type 56; Case 5, simulated by TRYNSYS; Case 6, calculated by SIMIEN the company; Case 7, simulated by Energyplus using thermal model CYPETHERME; Case 8, simulated by IDA Indoor Climate and Energy 4.8 (IDA- ICE). Reduction is calculated based on the same method.

Installation time elaboration: Case 3: installation of timber element, demolition works, removing of old windows, installation of load-bearing steel corners and base timber [28]; Case 4: installation and related works' time [33]; Case 5: installation of prefabricated panels [35]; case 6: On-site construction time [37]; Case 8: Prefab panels mounting at the building site including joints sealing (from internet search).

Cost comparison elaboration: Case 1: Investment cost difference between the best industrialised and traditional scenarios with same energy level target [21]; Case 3: Initial cost compared to ETICS renovation solution with rock wool insulation [29]; Case 6: The offered price for the works is compared to an estimate provided by the Norwegian carpenter's association of the cost for the same job executed as a traditional contract [39]; Case 8: Cost of the pilot building prefabricated wooden insulation panels compared to the cost of ETICS system insulation solution, which is preferred in the renovation market because of the lowest investment cost [49].

In addition to presenting building and system parameters, Fig. 2 offers a visual comparison of representative façade panels from each building project. Drawings and textual descriptions extracted from the reference were used to compile essential plan details of the panels, and diagrams were generated to illustrate the function of each layer [21], [22], [25], [30], [31], [35], [39], [41], [49]. In Case 1, due to a lack of detailed on-site panel information, a mock-up of a BIPV-integrated panel from the same project was used as a representative example. In Case 3, where corner connections are more common than continuous linear ones, a detail of a corner connection was selected to exemplify typical stratification.




L1 - Insulation; L2 - Insulated protective layer; L3 - Insulated levelling layer; L4 - Timber frame/stud; L5 - CLT panel; L6 - Cladding; L7 - Protective layer; L8 - Adjacent panel; L9 - Existing building

*Figure 2. Schematic layer stratification diagrams for each case (Not to scale)*

## 4 – ANALYSIS UNDER CIRCULAR ECONOMY PERSPECTIVE

This chapter presents a qualitative analysis of how each selected project aligns with circular economy (CE) design principles and the potential benefits brought by them. To structure this examination, a set of circular design criteria has been synthesized from several key sources in the field [5], [8], [50], [51]. Existing literature converges on broad objectives, and there is no universally accepted, standardized framework. Consequently, the specific principles applied here are selective and serve as a practical guide for evaluating these case studies. Due to varying documentation standards and performance indicators across projects, it is not feasible to conduct a strict quantitative comparison. In different cases, datasets include different metrics, which are reported according to the specific goals and methods of each project. As a result, the analysis relies primarily on qualitative descriptions and internal observations rather than cross-case numerical benchmarks.

Tab. 2 presents a subset of circular design strategies applicable at the component and material levels, extracted from the reference [8]. Eberhart et al. indicate that many of the summarized strategies overlap and are interconnected. Consequently, for the sake of brevity and analytical clarity, strategies deemed similar or not sufficiently represented in the case studies have not been included. Among the listed principles, 'prefabrication' is considered a fundamental criterion for case selection, and its characteristics and advantages have been thoroughly discussed; therefore, it will not be analysed separately.

### 4.1 Assembly/ disassembly

The development of Design for Disassembly (DfD) has become a key strategy in sustainable and circular design, and timber structures have been particularly emphasized in DfD, with potential environmental benefits like up to 99% reduction in GHG emissions per functional unit in life cycle assessment [52].

*Table 2: Selected circular design strategies from [8]*

| Circular design strategies | Description extracted from [8] |
|---|---|
| Assembly/ disassembly | Designing the building, components or materials to be easily assembled/disassembled. A precondition is reversible connections. |
| Material selection/ substitution | Choosing or substituting materials for materials that are e.g. local, renewable, natural/eco/bio, have lower environmental impact, of high quality, durable, easy assembly/disassembly, reusable and re-cyclable, pure, maintenance free, retain or increase their value, match the performance lifespan, non-toxic/ hazardous etc. |
| Prefabrication | Is used to ensure e.g. reclamation, reusability and recyclability, construction time optimisation, enhanced assembly and dis-assembly, enhanced adaptability,avoidance of off-cut materials etc. |
| Reusing existing building/ components/ materials | Is used to directly reuse existing buildings, components or materials for new construction projects. |
| Optimised shapes/ dimensions | Design to precise material measurements/specification in order to support more aspects of handling components and materials; enhance and enable future adaptability/flexibility. |
| Accessibility | Used to provide good access to connections between components to enhance design for assembly/disassembly, to ease maintenance, and maximise recovery of materials at end-of-life. |

As indicated in Tab. 2, reversible connections are a core requirement for this strategy. Industrialized panel systems nowadays typically incorporate a variety of components and functional layers; therefore, in such systems, connections encompass those between the panel and the existing building, between adjacent panels, and among the various functional components or layers within each panel. Fig. 3 depicts a schematic diagram outlining the panel's stratified layers and connections. In all selected cases, products interface with the existing building in ways that reflect connection reversibility—an approach that naturally suits prefabrication technologies. Simple, mass-produced metal components—such as steel plates and profiles secured with anchors, bolts, and screws—are widely employed in most cases, with the exceptions of Case 5 and Case 7. In Case 5, however, complex, high-performance customized steel components were utilized among panels to meet seismic reinforcement requirements, whereas Case 7 featured tongue-and-groove joints with insulation tape interposed. Tab. 3 summarizes connection types between the building and panels, and which among panels. It should be noted that this table is compiled based on the information listed in the reference, which may not capture all details, resulting in some incompleteness. Additionally, it represents only general information, as certain specialized component locations, such as corners, may feature unique construction methods.

From an installation standpoint, the benefits of such an approach are apparent. By reducing on-site work, the need for scaffolding diminishes, and occupants in some cases can stay in place, yielding social, economic, and environmental advantages. Case 3 reports that its on-site construction phase lasted only 10 weeks, in contrast to the five-to-six months required by traditional methods. Case 6 notes a total of 7 days and 10 hours for prefabricated panels mounting, with the entire building renovation on-site work finishing in 47 days and 10 hours, representing a 17% reduction in man-hours compared to conventional approaches.

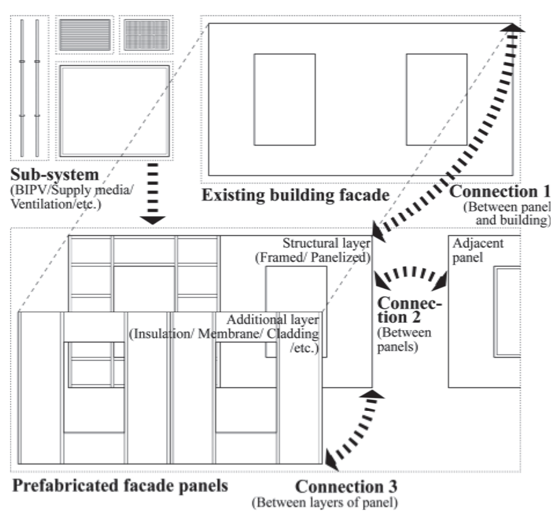



*Figure 3. Diagram of layers and connections within a prefabricated façade system for renovation*


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*Table 3: Connection types of cases*

| Case No. | Connection 1 | Connection 2 |
|---|---|---|
| 2 | BSC + MF | Vertical: BSC + MF + WJM<br>Horizontal: BSC + MF + CSC / FSC |
| 3 | BSC + MF | BSC + MF + FSC + FAF |
| 4 | BSC + MF + GFA | BSC + MF + FSC + FAF + GFA |
| 5 | BSC + MF | CSC + MF |
| 6 | BSC + MF | Unknown |
| 7 | BSC + MF | WJM + FAF |
| 8 | BSC + MF | BSC + MF + GFA |

BSC: Basic steel component (e.g. steel plate, L-Profile); MF: Mechanical fastener (e.g. screw, anchor, bolt); WJM: Wood joinery method (e.g. mortise-tenon joint, tongue-groove joint); CSC: Customized steel component; FSC: Flexible soft connector (e.g. EPDM gasket, rubber strip); FAF: Flexible adhesive film (e.g. tape, foil); GFA: Gap- filling adhesive (e.g. foam, sealant)

In Case 3, a prototype test took place roughly a year before the main renovation. The prototype façade components were dismantled and reused in the final project, requiring just 70 minutes to remove, demonstrating both disassembly feasibility and component reusability.

Economically, Case 6 indicates a roughly 15% lower overall cost relative to traditional methods, and estimates savings of approximately €910 per week per tenant by minimizing relocation requirements, amounting to a total of €116,480 over the course of the project. Overall, these examples demonstrate how the effective incorporation of reversible connections and efficient prefabrication practices can lead to tangible improvements in project management and the potential for component reuse.

## 4.2 Material selection/ substitution

As noted earlier, timber possesses several attributes that make it well-suited for renovation under a circular economy framework. However, when used as a primary structural material, timber's performance and end-of-life efficiency must be carefully considered, as it inherently exhibits limitations in fire resistance and hygrothermal performance; consequently, beyond the essential treatments required for structural applications, the stratification design within prefabricated panels becomes critical to mitigating these drawbacks—even though research indicates that the service life of timber is comparable to that of other construction materials [11]. Moreover, simulations using BIM models reveal that, although efficient connection designs can enhance timber's end-of-life reusability and recyclability, these metrics remain significantly lower than those observed for steel and concrete structures [13].

Beyond timber, insulation and cladding materials are also central to this strategy, given their substantial proportion in panels (as evidenced in Fig. 2) and the diverse range of available choices. Tab. 4 summarizes the cladding and insulation materials of selected cases.

For insulation material, case 2 employed wood fibre as insulation material, while case 4 partly used hardwood insulation (primarily made of wood fibre). Both are bio-based, offering circular advantages—including reduced toxicity, feasible reuse and recycling scenarios, and contributions to lignocellulosic waste management [53]. Meanwhile, the remaining cases used mineral wool or glass wool, which have comparatively favourable embodied energy/carbon profiles and end-of-life recyclability relative to other common insulation materials [54]. For instance, Case 7 presents a comparative analysis of the embodied energy of materials used in a traditional renovation solution and those employed in a plug-and-play panel system for the same building. The analysis indicates that substituting styrofoam with rock wool for insulation reduced the embodied energy of that component by 61%. However, variations in construction methods and material choices—particularly the increased use of timber and the inclusion of an additional protective layer (Fermacell HD) in the plug-and-play system—resulted in additional embodied energy [43]. Consequently, the overall reduction in embodied energy was limited to approximately 18%. In addition to the benefits mentioned above, Case 8 demonstrates that these materials offer excellent thermal insulation, robust fire resistance, moderate costs, and enhanced water vapour diffusion—qualities that not only make them outstanding performance-based choices for building renovation but also serve as effective supplements to improve the hygrothermal and fire resistance performance of timber structures [46].

*Table 4: Cladding and insulation material of cases*

| Case No. | Cladding material | Insulation material |
|---|---|---|
| 1 | unknown | Mineral wool |
| 2 | Ceramic panels | Wood fiber |
| 3 | Fiber cement panels and hot-oiled wooden cladding | Mineral wool |
| 4 | Wooden cladding | Glass wool + Hard wood insulation |
| 5 | Plaster | Rockwool |
| 6 | Solid wood based on slow-grown thermo-treated pine | Rockwool |
| 7 | Powerpanel (cement-based board) + plaster | Mineral wool |
| 8 | unknown | Mineral wool |

### 4.3 Reusing existing building/ components/ materials

Many of the prefabricated renovation solutions discussed in the case studies emphasize enhancing recycling and reuse prospects at a component's end-of-life. As noted in Section 4.2, the bio-based insulation materials employed—such as cellulose and wood fiber—are typically derived from wood-product waste streams (e.g., paper). Meanwhile, Case 3 demonstrates the direct reuse of prototype façade elements. This example suggests broader possibilities, such as using finger joints to connect short, recycled wood pieces into longer segments suitable for new components. In addition, 95% of the mineral wool insulation removed from the prototype was successfully reutilized, highlighting the potential for recovering and repurposing materials within prefabricated building systems.

### 4.4 Optimized shapes/ dimensions

An additional avenue for enhancing prefabricated solutions is optimizing façade geometry to minimize the number of panel prototypes and maximize standardization. Recent years have witnessed the emergence of BIM (Building Information Modelling) and 3D scanning technologies that provide precise measurements and digital models of existing buildings [55], [56]. In several of the selected cases, facade layout optimization emerges as a key strategy. Particularly in homogeneous structural systems without a beam-and-column framework (e.g. masonry and prefabricated panelised systems), greater freedom exists in how the façade is subdivided and anchored. For instance, Case 8 employed only 23 distinct panel sizes across approximately 2,000 $m^2$ of façade surface. Additionally, local transportation constraints dictated a maximum panel length of 9.969 m, adhering to a 10 m trucking limit. This streamlined approach not only simplifies off-site fabrication and on-site installation but also minimizes carbon emissions in the transportation phase, further supporting circular economy objectives.

### 4.5 Accessibility

As noted in Section 4.1, accessible connectors are inherently required in designs that facilitate assembly and disassembly. Given that most prefabricated panels are connected using additional metal connectors and considering that some connectors possess substantial vertical thickness—in part to fulfil mechanical or dissipative requirements—employing demountable components to cover these connections on the façade becomes a straightforward, convenient choice. In the selected case studies, Case 2 and Case 5 adopt this approach. Case 2 uses a prefabricated, insulating, removable panel in the vertical direction between two adjacent panels, secured below via a tongue-and-groove joint. Case 5 also installs a separate connector with EPS insulation and a waterproof membrane, making room to integrate water pipes and electrical conduits.

Beyond these external connections, accessibility is also crucial from the interior, especially since many prefabricated panels now incorporate HVAC, heating systems, and other equipment. Case 7, for instance, includes a complex internal design in which removable cover plates are installed on both sides of the interior surface. Steel profiles and gasketed aluminium profiles respectively seal the horizontal and vertical joints, enhancing thermal insulation and watertightness. While these accessible connections offer convenient maintenance and upgrade pathways, their insulation integrity and water-tight performance still require experimental verification to ensure long-term effectiveness.

## 5 – INSIGHT FOR AUSTRALIAN BUILDING STOCK

The Australian building stock faces challenges similar to those encountered internationally, like ambitious energy conservation and emission reduction targets, residential buildings that lag behind modern energy performance standards, and an urgently needed boost in renovation rates [57], [58]. This context creates fertile ground for the research and implementation of renovation strategies using prefabricated timber systems. Within Australia's residential housing stock, rental properties—which account for roughly one-third of the market and continue to grow—are generally of lower quality than owner-occupied dwellings [63]. This disparity stems largely from complex property rights and misaligned incentives between those who finance energy upgrades and those who ultimately benefit from them, rendering rental housing a key focus for energy retrofit initiatives. Furthermore, from the perspective of circular deep renovation, such projects typically demand substantial initial investments and must meet stringent energy upgrade standards that do not quickly yield short-term economic returns, thereby prolonging the payback period. In Australia, where private landlords are predominantly small-scale investors and governmental economic incentives for housing retrofits are relatively limited compared to Europe, the private rental sector faces significant challenges in implementing such retrofits [63]. Consequently, the most promising and feasible targets for circular deep renovation are rental properties that are government-owned or publicly managed, including social housing which also represents some of the poorest-quality dwellings in Australia [61]. It is estimated that 1% of the Australian population is affected by energy poverty; a substantial proportion of these households may reside in social housing, and the inability of providers to enhance the quality of their stock can have significant consequences for these vulnerable groups [60].

### 5.1 Structural similarity


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In the selected cases, all existing buildings incorporate structural components fabricated from brick and/or concrete. The structural performance analysis of Case 2 indicates that such structures exhibit robust residual capacity [24], rendering them well-suited to support additional façade panels. Furthermore, these materials facilitate reliable connections with the steel elements commonly employed in these projects. Analysis of material flows in the Australian housing industry from 1970 to 2020 indicates that Australia's building stock is predominantly composed of brick and concrete [59]. This alignment suggests that similar renovation systems have great potential for effective implementation in Australia.

### 5.2 Rapid, low-disruption retrofit strategies

Given the economic vulnerability of households in public or government-owned rental properties, retrofit strategies must prioritize rapid implementation and minimal disruption [62]. The inherent split incentives in the rental market and the high costs associated with temporary relocation further complicate energy upgrade efforts. Case studies suggest that prefabricated renovation systems are particularly effective in this context, as their expedited installation significantly reduces on-site construction duration and minimizes tenant displacement and relocation costs. Consequently, these systems facilitate enhanced energy performance and mitigate financial burdens on vulnerable households, thereby advancing broader social sustainability objectives.

### 5.3 Comprehensive upgrade approaches

Beyond the necessity of enhancing a building's thermal performance, poorly performing housing often faces additional issues related to overall living quality. These include low water-use efficiency, suboptimal energy efficiency in domestic hot water systems [3], and indoor mould problems stemming from inadequate ventilation [7]. Such issues are particularly prevalent in lower-quality rental apartments, the same as the targeted group of section 5.2. The case studies reviewed indicate that integrating ventilation devices, (e.g. mechanical fans), and water-related components (e.g. water tanks and hot water piping) within prefabricated systems is feasible. This integration offers a one-stop solution for comprehensive residential upgrades, thereby simplifying the overall renovation process while simultaneously addressing multiple performance deficiencies.

## 6 – Limitation and future work

This study faces several limitations. First, the data collection process was constrained by the available sources. Despite the existence of numerous outstanding international cases, many could not be incorporated into the analysis due to limitations in data accessibility and the fragmentary nature of the available information. Second, the absence of a standardized framework for data quantification and uniform statistical methodologies prevented an objective, cross-case comparison, resulting in a predominantly qualitative and subjective analysis.

Future work will involve further exploration of the opportunities and challenges of circular deep renovation in the Australian public-owned housing sector. The research plan includes an investigation into the design of circular renovation systems and technologies. In addition, efforts will focus on developing comprehensive circular renovation strategies and guidelines deriving from actual design, to establish a systematic framework for industry practitioners and policymakers.

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## 7 – REFERENCE

[1] '2022 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector', United Nations Environment Programme, Nairobi, 2022.

[2] M. Economidou, B. Atanasiu, and BPIE, Eds., Europe's buildings under the microscope: a country-by-country review of the energy performance of buildings. Brussels: Buildings Performance Institute Europe (BPIE), 2011.

[3] M. Marrero, C. Rivero-Camacho, and M. D. Alba-Rodríguez, 'What are we discarding during the life cycle of a building? Case studies of social housing in Andalusia, Spain', Waste Management, vol. 102, pp. 391–403, Feb. 2020, doi: 10.1016/j.wasman.2019.11.002.

[4] 'Towards the circular economy', Ellen MacArthur Foundation, 2013.

[5] A. González, C. Sendra, A. Herena, M. Rosquillas, and D. Vaz, 'Methodology to assess the circularity in building construction and refurbishment activities', Resources, Conservation & Recycling Advances, vol. 12, p. 200051, Dec. 2021, doi: 10.1016/j.rcradv.2021.200051.

[6] G. Romano, S. Baiani, F. Mancini, and F. Tucci, 'Reducing CO2 Emissions and Improving Water Resource Circularity by Optimizing Energy Efficiency in Buildings', Sustainability, vol. 15, no. 17, p. 13050, Aug. 2023, doi: 10.3390/su151713050.

[7] L. Bragança, M. Cvetkovska, R. Askar, and V. Ungureanu, Eds., Creating a Roadmap Towards Circularity in the Built Environment. in Springer Tracts in Civil Engineering. Cham: Springer Nature Switzerland, 2024. doi: 10.1007/978-3-031-45980-1.

[8] L. C. M. Eberhardt, M. Birkved, and H. Birgisdottir, 'Building design and construction strategies for a circular economy', Architectural Engineering and Design Management, vol. 18, no. 2, pp. 93–113, Mar. 2022, doi: 10.1080/17452007.2020.1781588.

[9] Y. She, N. Udawatta, C. Liu, and O. Tokede, 'Circular Economy-Related Strategies to Minimise Construction and Demolition Waste Generation in Australian Construction Projects', Buildings, vol. 14, no. 8, p. 2487, Aug. 2024, doi: 10.3390/buildings14082487.

[10] J. Konietzko, N. Bocken, and E. J. Hultink, 'Circular ecosystem innovation: An initial set of principles', Journal of Cleaner Production, vol. 253, p. 119942, Apr. 2020, doi: 10.1016/j.jclepro.2019.119942.

[11] M. H. Ramage et al., 'The wood from the trees: The use of timber in construction', Renewable and Sustainable Energy

Reviews, vol. 68, pp. 333–359, Feb. 2017, doi: 10.1016/j.rser.2016.09.107.

[12] Y. Niu, K. Rasi, M. Hughes, M. Halme, and G. Fink, 'Prolonging life cycles of construction materials and combating climate change by cascading: The case of reusing timber in Finland', Resources, Conservation and Recycling, vol. 170, p. 105555, Jul. 2021, doi: 10.1016/j.resconrec.2021.105555.

[13] L. A. Akanbi et al., 'Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator', Resources, Conservation and Recycling, vol. 129, pp. 175–186, Feb. 2018, doi: 10.1016/j.resconrec.2017.10.026.

[14] J. Monahan and J. C. Powell, 'An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework', Energy and Buildings, vol. 43, no. 1, pp. 179–188, Jan. 2011, doi: 10.1016/j.enbuild.2010.09.005.

[15] P. Mercader-Moyano and P. M. Esquivias, 'Decarbonization and Circular Economy in the Sustainable Development and Renovation of Buildings and Neighbourhoods', Sustainability, vol. 12, no. 19, p. 7914, Sep. 2020, doi: 10.3390/su12197914.

[16] N. Callegaro and R. Albatici, 'Energy retrofit with prefabricated timber-based façade modules: Pre- and post-comparison between two identical buildings', JFDE, vol. 11, no. 1, pp. 001–018, Dec. 2023, doi: 10.47982/jfde.2023.1.01.

[17] G. Evola, V. Costanzo, A. Urso, C. Tardo, and G. Margani, 'Energy performance of a prefabricated timber-based retrofit solution applied to a pilot building in Southern Europe', Building and Environment, vol. 222, p. 109442, Aug. 2022, doi: 10.1016/j.buildenv.2022.109442.

[18] R. Garay Martinez, J. Benito Ayucar, and B. Arregi Goikolea, 'Full scale experimental performance assessment of a prefabricated timber panel for the energy retrofitting of multi-rise buildings', Energy Procedia, vol. 122, pp. 3–8, Sep. 2017, doi: 10.1016/j.egypro.2017.07.288.

[19] R. Horne et al., 'Informing a strategy for circular economy housing in Australia', AHURI Final Report, no. 403, Jun. 2023, doi: 10.18408/ahuri5328001.

[20] G. Pernigotto (Ed.), F. Patuzzi (Ed.), A. Prada (Ed.), V. Corrado (Ed.), and A. Gasparella (Ed.), 'Building Simulation Applications BSA 2022', 2023, bu,press. doi: 10.13124/9788860461919.

[21] M. Gubert, S. Avesani, J. A. Ngoyaro, M. Juaristi Gutierrez, R. Pinotti, and D. Brandolini, 'Comparative cost analysis of traditional and industrialised deep retrofit scenarios for a residential building', JFDE, vol. 11, no. 2, pp. 145–168, Dec. 2023, doi: 10.47982/jfde.2023.2.A3.

[22] M. Pelle, M. Gubert, E. Dalla Maria, A. Astigarraga, S. Avesani, and L. Maturi, 'Experimental evaluation of the temperature related behaviour of pigment based coloured BIPV modules integrated in a ventilated façade', Energy and Buildings, vol. 323, p. 114763, Nov. 2024, doi: 10.1016/j.enbuild.2024.114763.

[23] C. Tardo, G. Fiore, and G. Margani, 'Technological analysis of prefabricated timber-based panels for the integrated renovation of RC framed buildings'.

[24] G. Margani, G. Evola, E. Marino, S. D'Urso, G. Nicolosi, C. Tardo, V. Costanzo, F. Barbagallo, C. Zagorianakos, T. Lerias, 'Detailed survey of the real pilot', e-SAFE Consortium (UNICT, SALFO), Deliverable D5.1, Feb. 2022. Accessed: Jan. 02, 2025. [Online]. Available: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5e8e2fac9&appId=PPGMS

[25] C. Halmdienst (PINK), B. Voortman (WEBO), M. Jansen(WEBO), 'Certificates of successful testing', e-SAFE Consortium, Deliverable D3.5, Nov. 2022. Accessed: Jan. 15, 2025. [Online]. Available: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5f3d3e6ac&appId=PPGMS

[26] S. D'Urso, G. Nicolosi, G. Evola, C. Tardo, V. Costanzo, G. Semprini, M. Liuzzo, I. M. Baratta, C. Zagorianakos, G. Margani, 'Report with the preliminary co-design outcome', e-SAFE Consortium (UNICT), Report D5.2, Jun. 2022. Accessed: Jan. 02, 2025. [Online]. Available: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5ed010437&appId=PPGMS

[27] D. Cottafava and M. Ritzen, 'Circularity indicator for residential buildings: Addressing the gap between embodied impacts and design aspects', Resources, Conservation and Recycling, vol. 164, p. 105120, Jan. 2021, doi: 10.1016/j.resconrec.2020.105120.

[28] K. Kuusk, K. Kullerkupp, P. Pihelo, M. Ritzen, A. Tisov, and T. Kalamees, 'Circularity concepts for offsite prefabricated energy renovation of apartment buildings', J. Phys.: Conf. Ser., vol. 2069, no. 1, p. 012074, Nov. 2021, doi: 10.1088/1742-6596/2069/1/012074.

[29] E. Nigumann, T. Kalamees, K. Kuusk, and P. Pihelo, 'Circular Renovation of an Apartment Building with Prefabricated Additional Insulation Elements to Nearly Zero Energy Building', sace, vol. 34, no. 1, pp. 22–34, Feb. 2024, doi: 10.5755/j01.sace.34.1.35674.

[30] T. Calabrese, D. Philippen, M. Neugebauer, I. Bosshard, and M. Haller, 'Renovation of a Multi-Family-House with External Wall Heating System', in Proceedings of EuroSun 2022 - ISES and IEA SHC International Conference on Solar Energy for Buildings and Industry, Kassel, Germany: International Solar Energy Society, 2022, pp. 1–12. doi: 10.18086/eurosun.2022.02.02.

[31 ]J. Colom, K. Tsoutis, M. Founti, 'Assembly methodology for PnU kits', PLURAL Consortium, Deliverable D6.2, Apr. 2023. Accessed: Jan. 15, 2025. [Online]. Available: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e504e6d2bd&appId=PPGMS

[32] J. Lucas, D. Romeu, M. Founti, 'Product requirement report', PLURAL Consortium (ITeC), Deliverable D8.1, Nov. 2023. Accessed: Jan. 15, 2025. [Online]. Available: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e504e6c99b&appId=PPGMS

[33] M. Colom, J. Colom, K. Tsoutis, M. Founti, 'Installation and in-situ validation methodologies', PLURAL Consortium, Deliverable D6.4, Apr. 2023. Accessed: Mar. 11, 2025. [Online]. Available: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e504949402&appId=PPGMS

[34] J. Zanni et al., 'Integrated Deep Renovation of Existing Buildings with Prefabricated Shell Exoskeleton', Sustainability, vol. 13, no. 20, p. 11287, Oct. 2021, doi: 10.3390/su132011287.

[35] J. Zanni et al., 'APPLICATION OF A WOODEN PREFABRICATED SHELL EXOSKELETON FOR THE INTEGRATED AND SUSTAINABLE RETROFIT OF A RESIDENTIAL BUILDING', in World Conference on Timber Engineering (WCTE 2023), Oslo, Norway: World Conference on Timber Engineering (WCTE 2023), 2023, pp. 4173–4181. doi: 10.52202/069179-0543.

[36] J. Zanni et al., 'Application of CLT prefabricated exoskeleton for an integrated renovation of existing buildings and continuous structural monitoring', Procedia Structural Integrity, vol. 44, pp. 1164–1171, 2023, doi: 10.1016/j.prostr.2023.01.150.

[37] R. Pinotti, K. Thunshelle, K. Andresen, H. Høilund-Kaupang, I. F. Riverola, M. V. Gomez, C. Ferrer, C. Boonstra, W. Bakker, 'Concept design and performance targets for the demos', 4RinEU Consortium (EURAC), Deliverable D5.2, Mar. 2020. Accessed: Jan. 13, 2025. [Online]. Available: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5cea4d86f&appId=PPGMS

[38] A. Werner, K. Thunshelle, R. Pinotti, 'Cost-effectiveness rating system', 4RinEU Consortium (SINTEF), Deliverable D4.2, Nov. 2020. Accessed: Jan. 13, 2025. [Online]. Available: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5d65e6cc0&appId=PPGMS

[39] R. Pinotti, K. Thunshelle, K. Andresen, H. Høilund-Kaupang, I. F. Riverola, M. V. Gomez, C. Ferrer, C. Boonstra, W. Bakker, L. Civalleri, 'Report on deep renovation packages

 https://doi.org/10.52202/080513-0564

as tailored and implemented in the demo cases', 4RinEU Consortium (ACCIONA), Deliverable D5.3, Jun. 2021. Accessed: Jan. 22, 2025. [Online]. Available: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5ded9dc6c&appId=PPGMS

[40] P. Dymarski, R. Bornemann, S. Barberis, A. Łukaszewska, M. Dabek, A. Vervoort, A. Gralka, 'Sets of PnP prefab components for building envelopes', P2ENDURE Consortium (Mostostal Warszawa S.A.), Deliverable D1.1, Aug. 2017. Accessed: Jan. 13, 2025. [Online]. Available: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5b8319021&appId=PPGMS

[41] P. Dymarski, R. Bornemann, A. Vervoort, A. Bogacz, A. Łukaszewska, M. Arnesano, O. Terpstra, E. Willems, 'Designs of integrated packages of deep renovation solutions', P2ENDURE Consortium (Mostostal Warszawa S.A.), Deliverable D1.2, Aug. 2019. Accessed: Jan. 26, 2025. [Online]. Available: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5c797671b&appId=PPGMS

[42] L. Visser, E. Willems, M. Arnesano, A. Gralka, 'Baseline report of pre-renovation condition of demonstration cases', P2ENDURE Consortium (Huygen Installatie Adviseurs), Deliverable D4.1, Feb. 2020. Accessed: Jan. 13, 2025. [Online]. Available: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5cccc048d&appId=PPGMS

[43] E. Willems, A. Dedeoglu, 'Validation report of lowered embodied energy at prefab renovation projects', P2ENDURE Consortium (Huygen Installatie Adviseurs B.V.), Deliverable D3.2, Feb. 2020. Accessed: Jan. 13, 2025. [Online]. Available: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5cc9857b1&appId=PPGMS

[44] M. B. Dzik, A. Łukaszewska, M. Gilu, 'Validation report of replicability and scalability of PnP prefab solutions', P2ENDURE Consortium (FASADA sp. z o.o.), Deliverable D3.4, Feb. 2020. Accessed: Jan. 13, 2025. [Online]. Available: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5ccb2a539&appId=PPGMS

[45] G. Bizzarri, L. Ferrari, B. Turilazzi, L. Fumelli, E. Mainini, M. Arnesano, 'Validation report of reduced use of net primary energy', P2ENDURE Consortium (Becquerel Electric srl), Deliverable D3.1, May 2020. Accessed: Jan. 26, 2025. [Online]. Available: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5cf4ff88b&appId=PPGMS

[46] M. Volf, P. Hejtmánek, A. Lupíšek, T. Kalamees, F. Christensen, S. Olesen, J. A. W. H. van Oorschot, O. C. Mørck, A. Borodinecs, P. Šenfeldr, 'A set of basic modular facade and roof elements including renewable energy production and integration of HP insulation', MORE-CONNECT Consortium (Czech Technical University in Prague), Deliverable D2.2, Oct. 2018. Accessed: Jan. 13, 2025. [Online]. Available: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5be2efe5d&appId=PPGMS

[47] R. Bolliger, W. Ott, A. Borodinecs, M. Almeida, R. Mateus, A. Mestre, A. Lupíšek, M. Volf, T. Vlach, T. Kalamees, K. Kuusk, P. Pihelo, R. Rovers, B. Voortman, S. Olesen, F. Christensen, 'Guide of material alternatives in relation to reuse and the combined energy and materials impact of prefabricated elements', MORE-CONNECT Consortium (econcept AG), Deliverable D3.5, Oct. 2017. Accessed: Jan. 13, 2025. [Online]. Available: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5b6b9d52e&appId=PPGMS

[48] A. Hamburg, K. Kuusk, A. Mikola, and T. Kalamees, 'Realisation of energy performance targets of an old apartment building renovated to nZEB', Energy, vol. 194, p. 116874, Mar. 2020, doi: 10.1016/j.energy.2019.116874.

[49] K. Kuusk, P. Pihelo, and T. Kalamees, 'Renovation of apartment buildings with prefabricated modular panels', E3S Web Conf., vol. 111, p. 03023, 2019, doi: 10.1051/e3sconf/201911103023.

[50] N. M. P. Bocken, I. De Pauw, C. Bakker, and B. Van Der Grinten, 'Product design and business model strategies for a circular economy', Journal of Industrial and Production Engineering, vol. 33, no. 5, pp. 308–320, Jul. 2016, doi: 10.1080/21681015.2016.1172124.

[51] M. Moreno, C. De Los Rios, Z. Rowe, and F. Charnley, 'A Conceptual Framework for Circular Design', Sustainability, vol. 8, no. 9, p. 937, Sep. 2016, doi: 10.3390/su8090937.

[52] M.-N. David, R.-S. Miguel, and P.-Z. Ignacio, 'Timber structures designed for disassembly: A cornerstone for sustainability in 21st century construction', Journal of Building Engineering, vol. 96, p. 110619, Nov. 2024, doi: 10.1016/j.jobe.2024.110619.

[53] C. Rabbat, S. Awad, A. Villot, D. Rollet, and Y. Andrès, 'Sustainability of biomass-based insulation materials in buildings: Current status in France, end-of-life projections and energy recovery potentials', Renewable and Sustainable Energy Reviews, vol. 156, p. 111962, Mar. 2022, doi: 10.1016/j.rser.2021.111962.

[54] D. Kumar, M. Alam, P. X. W. Zou, J. G. Sanjayan, and R. A. Memon, 'Comparative analysis of building insulation material properties and performance', Renewable and Sustainable Energy Reviews, vol. 131, p. 110038, Oct. 2020, doi: 10.1016/j.rser.2020.110038.

[55] M. P. Aldanondo, J. Lesbegueries, A. Christophe, E. Vareilles, and X. Lorca, 'Building insulation renovation: a process and a software to assist panel layout design, a part of the ISOBIM project.', presented at the 40th International Symposium on Automation and Robotics in Construction, Chennai, India, Jul. 2023. doi: 10.22260/ISARC2023/0008.

[56] K. Iturralde, E. Gambao, and T. Bock, 'Semiautomated Primary Layout Definition with a Point Cloud for Building-Envelope Renovation', Buildings, vol. 14, no. 2, p. 351, Jan. 2024, doi: 10.3390/buildings14020351.

[57] S. Seo and G. Foliente, 'Carbon Footprint Reduction through Residential Building Stock Retrofit: A Metro Melbourne Suburb Case Study', Energies, vol. 14, no. 20, p. 6550, Oct. 2021, doi: 10.3390/en14206550.

[58] P. Rajagopalan, D. Chen, and M. Ambrose, 'Investigating envelope retrofitting potential and resilience of Australian residential buildings – A stock modelling approach', Energy and Buildings, vol. 325, p. 114990, Dec. 2024, doi: 10.1016/j.enbuild.2024.114990.

[59] T. Dalton et al., 'Building materials in a circular economy', AHURI Final Report, no. 402, Jun. 2023, doi: 10.18408/ahuri5328401.

[60] J. Halldorsson, E. Liu, D. Daly, P. McGuirk, B. Judd, P. Cooper, G. Waitt, J. Gardner, 'Energy efficiency in social housing: Literature and program review', Department of Planning, Industry and Environment (NSW Government), Parramatta, NSW, Australia, EES 2020/0483, Oct. 2020. Accessed: Mar. 23, 2025. [Online]. Available: https://www.energy.nsw.gov.au/sites/default/files/2022-09/energy-efficiency-in-social-housing-literature-and-program-review-200483.pdf?

[61] E. Baker, T. Moore, L. Daniel, R. Caines, H. Padilla, and L. Lester, 'Sustainable social housing retrofit? Circular economy and tenant trade-offs', AHURI Final Report, no. 397, May 2023, doi: 10.18408/ahuri3128301.

[62] S. Haddad, R. Paolini, A. Synnefa, L. De Torres, D. Prasad, and M. Santamouris, 'Integrated assessment of the extreme climatic conditions, thermal performance, vulnerability, and well-being in low-income housing in the subtropical climate of Australia', Energy and Buildings, vol. 272, p. 112349, Oct. 2022, doi: 10.1016/j.enbuild.2022.112349.

[63] T. W. Heffernan, E. E. Heffernan, N. Reynolds, W. J. (Thomas) Lee, and P. Cooper, 'Towards an environmentally sustainable rental housing sector', Housing Studies, vol. 36, no. 3, pp. 397–420, Mar. 2021, doi: 10.1080/02673037.2019.1709626.