REPORT

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WHOLE-LIFE CARBON AND INDUSTRIAL RENOVATION

REALISING THE OPPORTUNITIES TO REDUCE THE LIFECYCLE CARBON FOOTPRINT OF BUILDINGS

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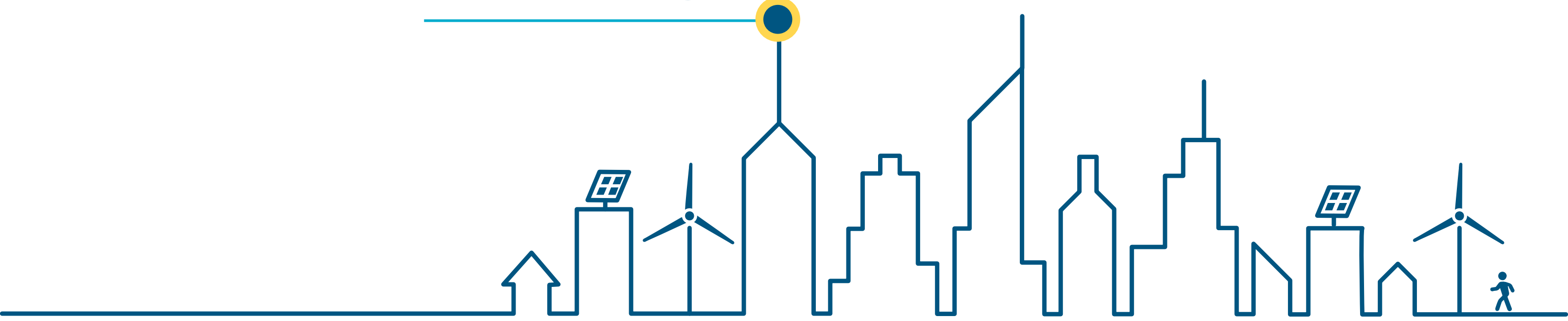

EXECUTIVE SUMMARY

To reach the European climate targets set out in the Fit for 55 package and Renovation Wave, carbon emissions must be cut by 55% compared to 1990 levels [1]. Building construction and operations are responsible for 36% of carbon emissions in the EU. The latest European Commission proposal therefore aims to achieve a 60% emission reduction by 2030 for the building sector, compared to 2015 levels [2]. Significant building improvements and renovations will need to occur to realise this ambitious goal.

While several conventional measures exist for building renovations, innovative solutions are needed to meet climate targets. Industrial prefabrication has the potential to substantially increase the renovation rate, and decrease energy use and emissions. Industrial prefabrication for renovation is the process of producing integrated renovation solutions, such as roof or façade systems, in factories to reduce construction time on-site. To realise the full potential of industrial prefabrication and accelerate the decarbonisation of the building stock, it is important to make use of levers that push industrial prefab solutions and the reduction of whole-life carbon (WLC) emissions at the same time.

Whole-life carbon considerations and industrial prefabrication are mutually reinforcing in numerous ways. Five promising opportunities to leverage both the whole-life carbon impact of renovation and industrial prefabricated renovation solutions are:

1. Innovation in design
2. Resource efficiency (transport, streamlined delivery processes, low carbon materials and elimination of waste)
3. Quality assurance
4. Lifecycle costing
5. Circular business models

This paper focuses on these opportunities and provides recommendations for policymakers aiming to create an optimal policy framework to reduce emissions from buildings while fostering innovation in the renovation sector.

The report concludes with recommendations to increase the uptake of industrial prefabrication and foster whole-life carbon reduction strategies:

- Digital solutions are key to innovation in the building sector, in particular to enable industrial prefabrication and to design and implement renovations with lower whole-life carbon impact. Supporting the interoperability and use of digital tools like building information modelling, lifecycle analysis software and digital building logbooks will increase transparency and ease of communication and storage of environmental data.
- The Energy Performance of Building Directive should emphasise whole-life carbon measures, including by linking the zero-energy building definition to whole-life carbon, defining whole-life carbon integration milestones towards 2050, and linking minimum energy performance standards to whole-life carbon.

- The Construction Products Regulation should align 2050 targets by fostering improved quality of environmental data for construction products in the EU and mandate the use of environmental product declarations.

- The EU and Member States should provide targeted funding, subsidies and tax breaks for industrial prefabrication of renovation solutions that account for whole-life carbon.

ABBREVIATIONS

- **BIM** Building information modelling
- **EPBD** Energy Performance of Buildings Directive
- **EPD** Environmental product declaration
- **LCA** Life cycle assessment
- **BIM** Building information modelling
- **WLC** Whole-life carbon

INTRODUCTION

Current EU initiatives and policies are calling for ambitious reductions in energy use and greenhouse gas emissions. Buildings play a critical role in the EU's decarbonisation efforts, so significant focus needs to be put on solutions to renovate the building stock and future-proof EU infrastructure. The Renovation Wave states that the EU must double the average annual energy renovation rate from the current rate of 1% to 2% by 2030.

Although the increase in ambition is essential, even more effort is required to meet EU climate targets. According to a BPIE analysis, the deep renovation rate[1] should increase to at least 3% as soon as possible to achieve our climate targets. The Fit for 55 package outlines ambitious European climate targets for 2030, including a 60% reduction of building sector emissions compared to 2015. The recent introduction of REPowerEU has further increased the ambition and the pace of phasing out EU dependency on Russian fossil fuels by 2027, for which demand reduction will need to play a large role [3].

1 "Deep renovation" refers to renovations leading to a decrease of primary energy need of at least 60%; a range of 75-90% would be in line with 2030 EU climate targets according to BPIE analysis.

Beyond meeting EU targets, renovating the EU building stock has the potential to significantly increase quality of life, lower energy use and emissions, and create jobs. Several initiatives and measures are in place to help achieve significant energy savings and reduced emissions in the building sector, but tools are needed to either enhance current efforts or create new, innovative solutions to realise the full decarbonisation potential of the EU building stock, and future-proof European infrastructure. Industrial prefabrication for renovation, the process where complete building parts or modules are manufactured off-site and installed on the construction site, is a potential solution to increase renovation rates.

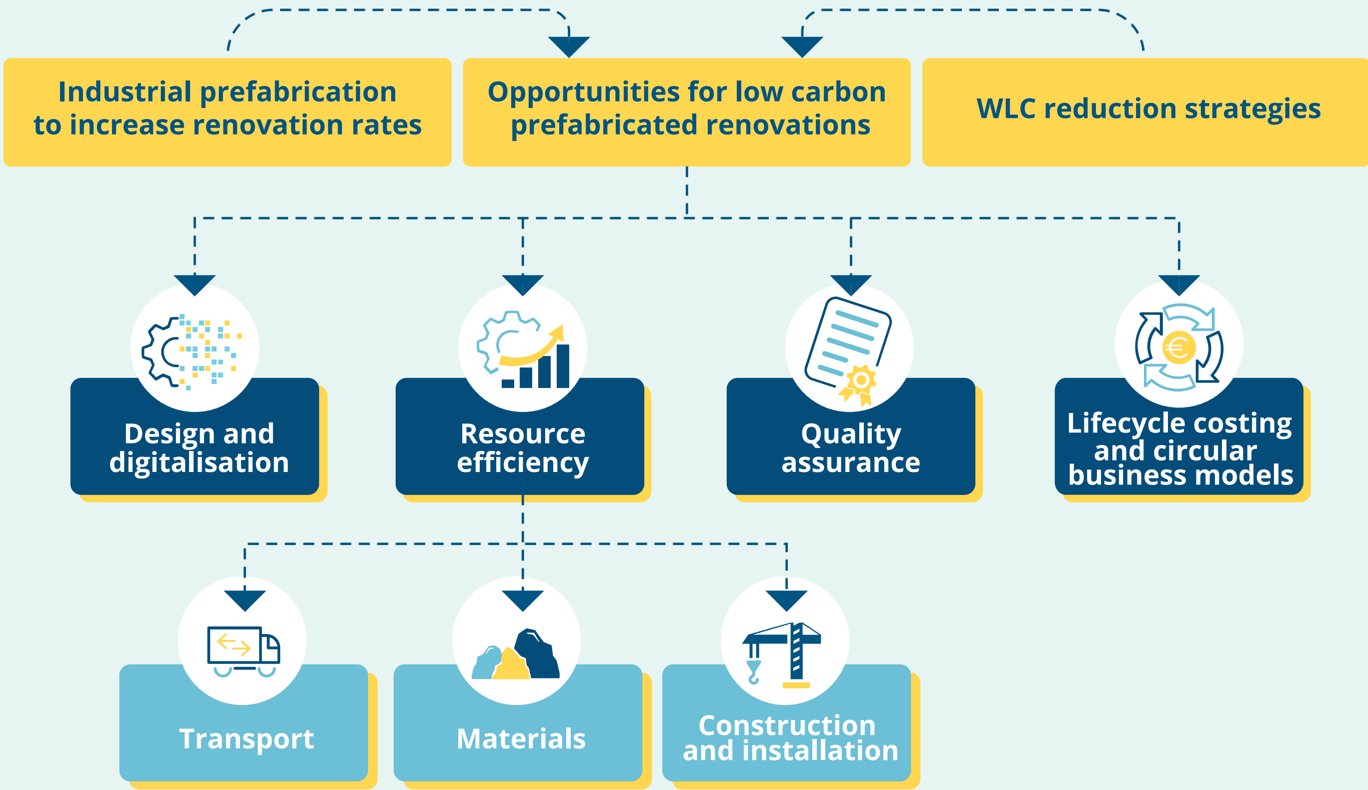

Figure 1 - The intersection of industrial prefabrication and whole-life carbon to create low-carbon renovation solutions.

As case studies show, prefabrication as a production method in itself is not sufficient to ensure lower embodied and operational emissions of (new) buildings, as it is possible to prefabricate highly inefficient buildings with high embodied carbon materials. Therefore, it is important to identify and incorporate emissions reduction potential during the whole-life of a prefabricated building or renovation (i.e., whole-life carbon). Several strategies exist to implement whole-life carbon (WLC) reduction strategies within industrial prefabrication of renovations (see figure 1).

This paper looks at the potential synergies between industrial prefabrication processes and WLC to decarbonise the building stock.

INDUSTRIAL PREFABRICATION AND WHOLE-LIFE CARBON

INDUSTRIAL PREFABRICATION: A SHORT BACKGROUND

Industrial prefabrication entails producing integrated renovation solutions, such as roof or façade systems, in factories to reduce construction time on-site. Although the methods used for prefabrication currently are mostly applied to new buildings, there are numerous industrial renovation programmes and pilot projects across the EU. Approaches such as Energiesprong show the potential of industrial prefabrication to disrupt the renovation market, bringing needed innovation and increasing the renovation rate for specific building typologies.

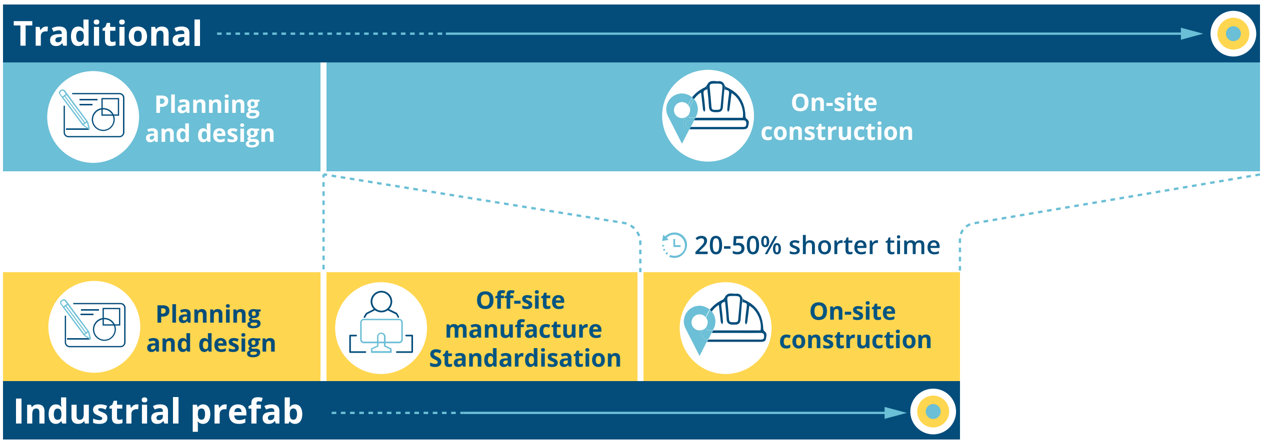

Figure 2 - Timeline of traditional construction process vs. industrial prefabrication

Since industrial prefabrication involves a different way of constructing or renovating buildings, there are significant benefits for process improvements, resource efficiency, cost savings and quality control. Prefabrication is already applied widely in the construction of new buildings within the EU [4], but is less common in the renovation sector. Despite the perceived increased complexity of industrial prefabrication of renovations, examples like P2Endure, Energiesprong, or MoreConnect illustrate that prefabricated renovation solutions are suitable for delivering high-performance renovations with potential to scale. Industrial prefabrication of renovation solutions has several potential benefits [5]:

- Lower and more predictable total project costs.
    - Fewer mistakes on-site can save an estimated 5-10% in costs [5].
    - Standardisation through digitalisation and process optimisation can reduce the costs by up to 25% compared to a conventional renovation approach [6].
- Lower labour costs.
- Shorter on-site construction time and less disturbance for tenants.
    - Prefabrication in a factory can shorten construction time by 18%.
    - One prefabricated module of 20m^2 takes on average just one hour for three workers to install on-site [7].
    - A prefabrication approach decreases the duration of the overall renovation process by 25-44% [6].
- Reduced health and safety risk on the construction site.
- Increased resource efficiency.

An important difference between conventional and industrially prefabricated solutions is the construction process itself. Construction in a factory requires more initial planning and more accurate design, different skills of building professionals and different construction processes compared to on-site construction. Next to these changes, the investment in new factories and the need to produce the complete building or unit upfront before it can be installed require a longer-term and stable pipeline of projects to be profitable. Combined, these changes in working processes and additional complexity pose a challenge for industrial prefabrication.

More predictable, less disruptive and more affordable renovations can be attractive to building owners, besides having potential to improve the energy performance of buildings and meet climate targets for buildings. Additionally, industrial prefabrication has synergies with whole-life carbon accounting, as will be explained below, which can further add to the environmental benefits.

WHOLE-LIFE CARBON: A SHORT BACKGROUND

Carbon emissions are generated during several phases of building construction and use, all of which need to be reduced to achieve a fully decarbonised building stock. Emissions generated during building use are known as operational carbon emissions, and are caused by heating, cooling and electricity use in a building. Embodied carbon emissions are emissions associated with materials and construction processes used throughout the lifecycle of a building (or infrastructure) (see figure 2) [8].

Definition | Meaning

Whole-life carbon = Embodied emissions + operational emissions

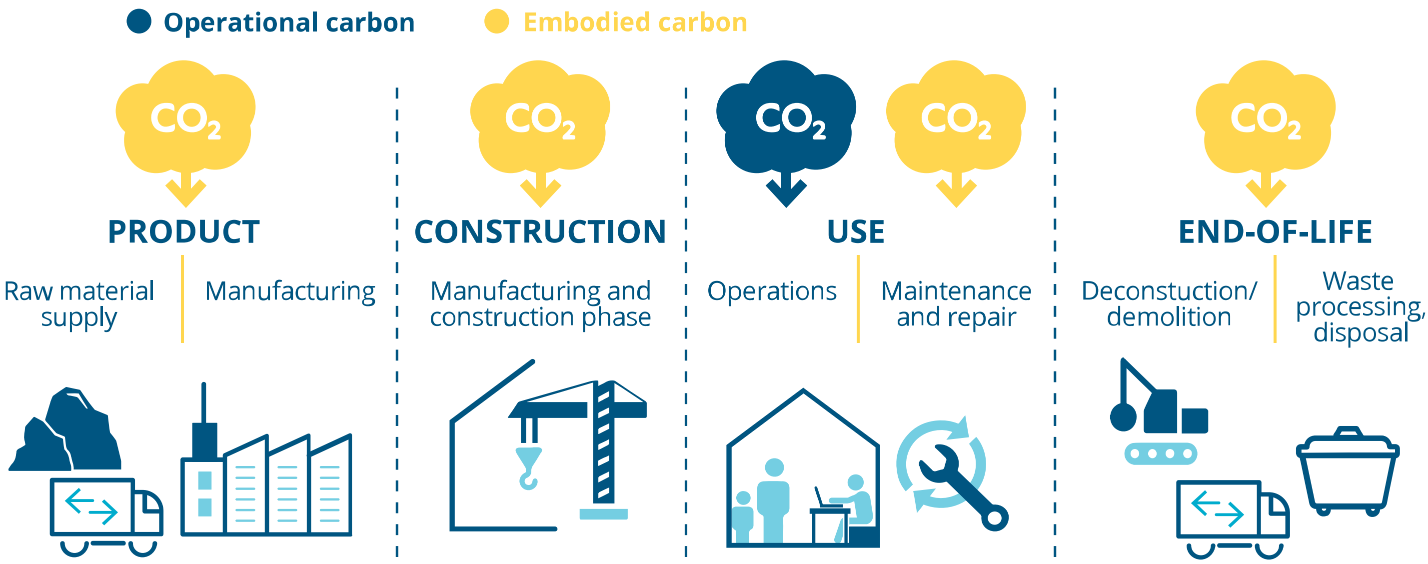

Figure 3 - Operational and embodied emissions [9].

Building regulations have typically focused on operational CO_2 emissions, rather than the entire lifecycle of a building.[2] Currently, the average embodied emissions of buildings compliant with modern building standards account for 20-25% of the total lifecycle emissions [10] – but this proportion will increase as operational emissions fall.

[2] There are exceptions, most notably Denmark, which will regulate whole-life carbon from 2023. See https://www.bpie.eu/wp-content/uploads/2021/05/BPIE_WLC_Summary-report_final.pdf.

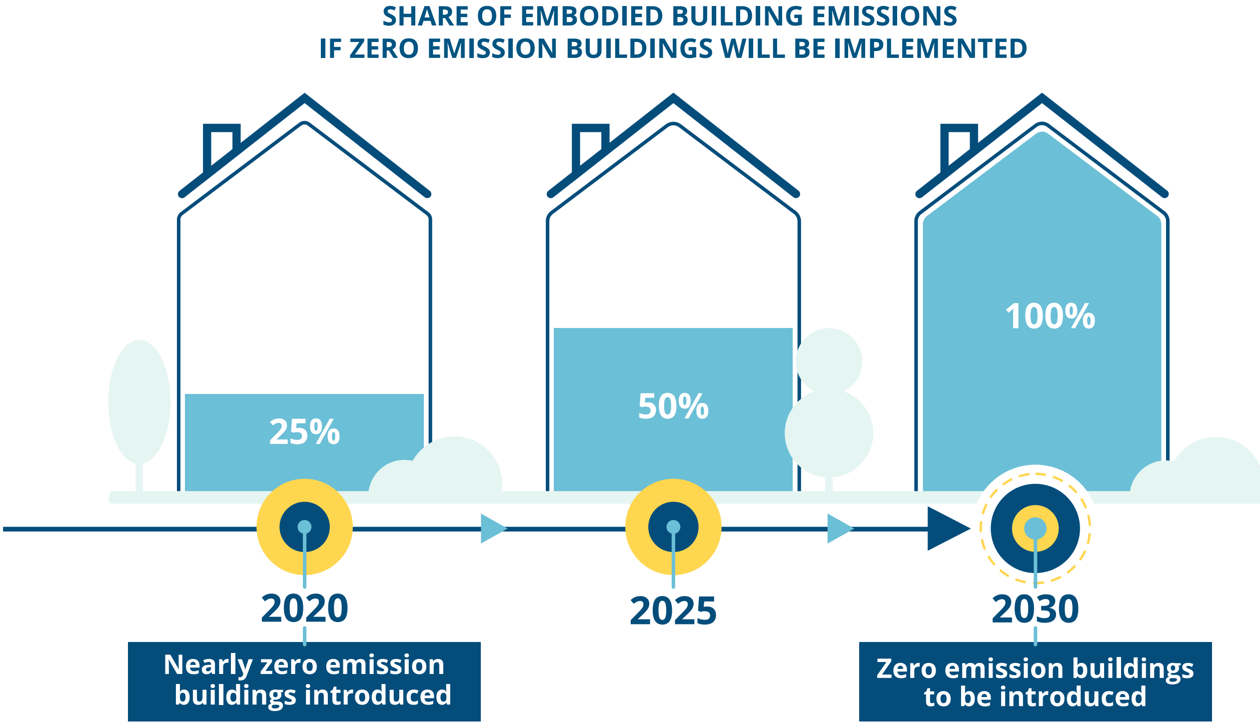

Figure 4 - The share of embodied building emissions covered if zero emissions buildings are implemented.

According to the recent recast proposal of the Energy Performance of Buildings Directive (EPBD), the near-zero energy building standard currently applicable for new buildings will evolve into the zero-emission building standard in 2030 [34]. If the proposed EPBD amendments are adopted, the operational emissions of a new building must be reduced to zero, which means that most emissions will become embodied. As emissions during the operational phase are reduced to (almost) zero over the coming decades, most emissions will be emitted during the manufacturing, construction, maintenance, renovation and disposal/deconstruction of buildings. National authorities and the European Commission are therefore considering the introduction of WLC measurement and reporting requirements before setting target and limit values for lifecycle emissions.

Benchmarking studies of whole-building lifecycle assessments (LCAs), looking at both embodied and operational emissions of hundreds of European buildings, show that for highly energy-efficient buildings built in 2020, the share of embodied carbon is already 45-50% and up to 90% in extreme cases [10]. This ratio is bound to shift further towards embodied emissions when the building systems, heating supply and electricity grid decarbonise further. This illustrates that solely focusing on the operational emissions would miss significant sources of emissions and highlights the need to reduce emissions over the complete lifecycle of buildings.

WHAT IS A WHOLE-LIFE CARBON ASSESSMENT?

WHOLE-LIFE CARBON ASSESSMENTS INVOLVE ASSESSING THE OPERATIONAL EMISSIONS GENERATED THROUGH LIGHTING, HEATING, COOLING AND POWERING BUILDINGS, AS WELL AS EMBODIED EMISSIONS ASSOCIATED WITH CONSTRUCTION PROCESSES AND CONSTRUCTION MATERIALS THROUGHOUT THE WHOLE LIFECYCLE OF A BUILDING [13].

The next step in regulation, which certain Member States have already announced for coming years, is to set an embodied emissions ceiling for construction projects. Construction companies, architects and manufacturers are anticipating these upcoming changes and have developed methods to reduce embodied carbon in construction materials and construction processes [13] besides designing end-of-life solutions focusing on reuse and circularity. To anticipate the expected WLC regulations this decade and make industrial prefabrication future-proof it is essential to integrate WLC into industrial prefabrication renovation approaches.

INDUSTRIAL PREFABRICATION OPPORTUNITIES TO REDUCE WHOLE-LIFE CARBON OF RENOVATION SOLUTIONS

While this section identifies opportunities for WLC to be integrated into industrial prefabrication, most arguments and case studies are based on prefabrication in construction of new buildings, because of the relatively small amount of prefabricated renovation solutions. Nevertheless, it can be assumed that benefits applicable to new builds can partially apply to renovations.

Several opportunities exist to minimise CO_2 emissions within the industrial prefabrication renovation process during the building lifecycle:

- **Design** – low-carbon materials, integrating end-of-life scenarios, in-use performance, process optimisation, design for extended lifetime, flexibility, adaptability and sufficiency.
- **Product stage** – using low-carbon materials and materials with longer lifetimes to increase overall resource efficiency.
- **Construction stage** – process optimisation and improved quality assurance.
- **Use phase** – better quality assurance can improve performance and extend lifetime of renovation solutions.
- **End of life** - reuse and recycling, contributing to circular economy strategies.

When looking at the lifecycle of a construction project, in each life phase different strategies to reduce WLC apply.

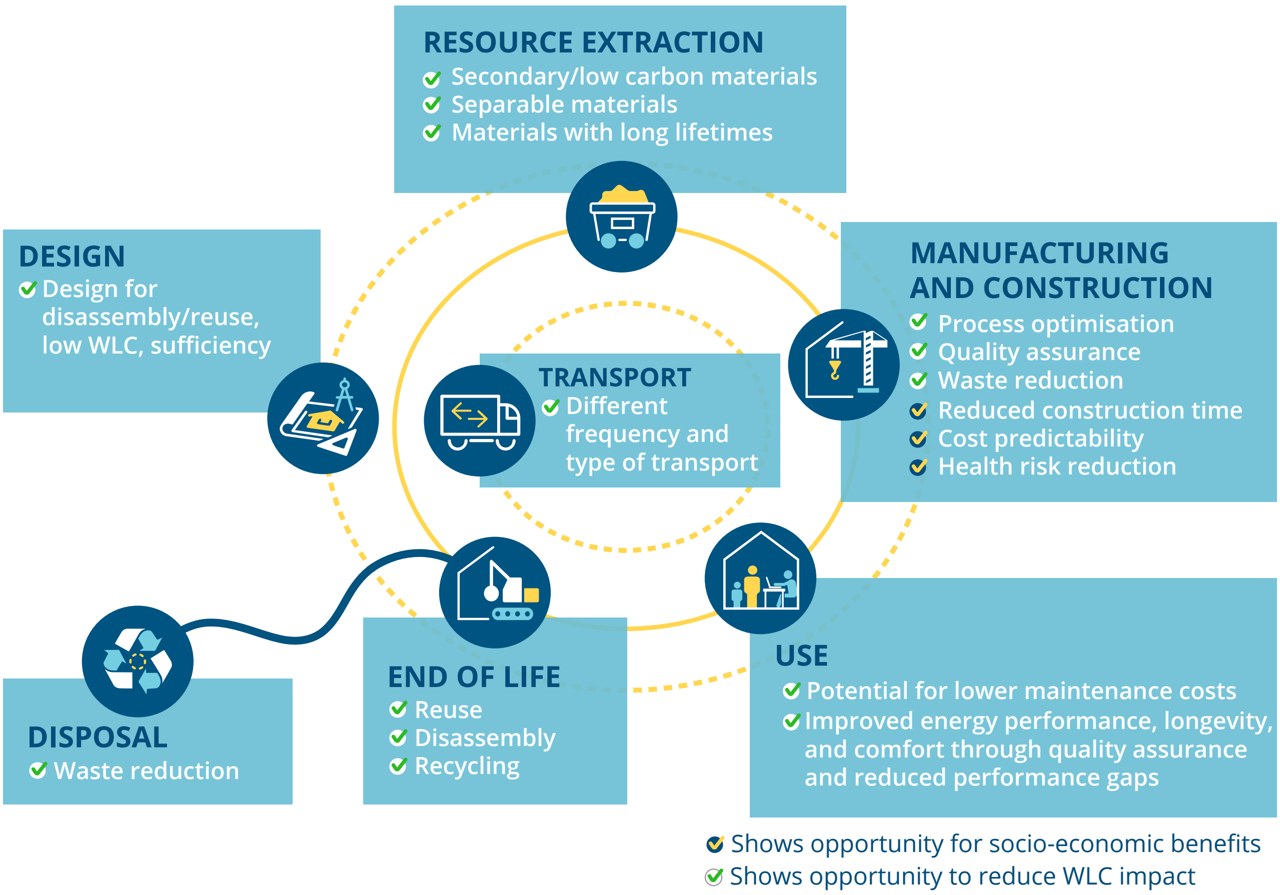

Figure 5 - Industrial prefabrication process and opportunity to reduce WLC impact.

Numerous strategies exist to optimise WLC performance of construction and renovations, many of which can be applied to industrial prefabrication. The following section discusses several important strategies and focuses particularly on a) design, b) resource efficiency, c) quality assurance, and d) lifecycle costing and circular business models. Finally, insights from several case study research projects are analysed.

DESIGN AND DIGITALISATION

Design is key to integrating and optimising WLC in industrial prefabricated solutions for renovations. Digitalisation and process optimisation can reduce costs by up to 25% [14]. Designs of industrially prefabricated renovation solutions must take the complete lifecycle of a building into account to fully decarbonise buildings and anticipate stricter future WLC regulations. To achieve that, digitalisation of the renovation process is essential to enable architects to improve the quality of designs and optimise WLC impact of renovation solutions. Building information modelling (BIM[3]), availability of carbon and environmental data of construction products, and digital building logbooks as central data repositories are of relevance to optimise WLC in industrial prefabrication renovation design. Combining digital tools like BIM and digital building logbooks with quality data provides a an overview and repository to track building components.

BIM as a key tool to optimise whole-life carbon in renovation design

BIM has the potential to optimise WLC performance as it allows comparison of different design choices, for example the ability to compare the embodied carbon of different façade types or load-bearing structures. Architects use BIM to develop a digital model of the building, including material inventories, which they can use to calculate the environmental impact of materials. Digital plug-ins of LCA tools into BIM could allow architects to compare the impact of construction materials and the design of building parts while accounting these impacts for the complete lifecycle. In addition, BIM-based whole-life performance estimators have been developed that allow architects and designers to estimate the reusability of their designs at the end of the building's life [15].

Using BIM data for evaluation purposes, industrially prefabricated new buildings have already been designed with lower WLC emissions compared to conventional construction [16]. Allowing building parts to be reused is an important step in the creation of a building sector circular economy, in addition to avoiding the manufacturing of unnecessary building parts – contributing to sufficiency [18]. This illustrates the potential of industrial prefabrication to improve the reusability of building parts and thereby reduce the WLC impact.

Another advantage of BIM is its potential for data storage. BIM makes it easier to log materials and their carbon and environmental properties and store these digitally. The data concerning materials and designs can be exported and saved, for example in digital building logbooks. This has potential to improve communication and transparency of environmental performance of new buildings and renovations between different actors in the building value chain.

[3] Building information modelling: BIM is the creation of a digital model of a building, combining several information "layers" concerning the construction materials, the HCAV systems, water systems, wiring all together into one 3D building model.

Challenges and opportunities of reducing whole-life carbon by integrating environmental data in BIM workflows

Trustworthy, harmonised and digital environmental data from construction products is key to evaluate the impact of specific construction products and installations. Environmental product declarations (EPDs) are the primary source of environmental data and carbon emissions in the construction sector. EPDs are standardised summaries of LCAs presenting the environmental impact of a product. For example, an EPD of a cubic metre of concrete or wood contains the estimated impact over several lifecycle phases of the product, including its carbon emissions. It is obligatory to include the material extraction, manufacturing and transport phases. Starting in 2022, manufacturers must also include an end-of-life scenario.[4]

One limitation of EPDs is that the comparison between products remains challenging. While it can be useful to compare LCAs of products with similar functions, such as two types of insulation, comparing products with different functions (e.g., insulation vs. loadbearing structure) can be like comparing apples and oranges due to different product lifetimes, requirements and so on. The complete lifecycle impact of construction products also depends on the overall performance of the building, including its performance during the operational phase, based on how the totality of construction products shaping the building function together. As such, comparing different construction products' EPDs is challenging. This is why LCAs of whole buildings are key to assess the WLC performance of buildings and products [18]. This is where BIM could prove valuable under the right conditions. With automated interoperability between LCA-software and BIM and verified EPDs as an environmental data source, it could be possible for architects to compare design scenarios and choose low WLC options [18]. Linking the BIM workflow with LCA tools is therefore a promising strategy to reduce the WLC impact for industrially prefabricated renovation solutions.

Digital building logbooks as data repositories supporting circular design and disassembly

Digital building logbooks are digital data repositories that allow the storage of building data over the lifetime of a building. Digital building logbooks can store a wide range of information, combining essential environmental building information (EPDs, material passports, whole-building LCAs), energy information (energy performance certificates), building renovation passports, and information on the reusability of materials at end of life (enabling estimates of the residual value of buildings) [8]. All of this is essential information that can help all stakeholders along the value chain decide and track which materials to use to reduce overall emissions.

This multifunctional nature makes digital building logbooks a useful tool for industrial prefabrication and WLC impact reduction. Laser scanners can be used to create a digital model of the existing building to be renovated in a BIM environment, which can be saved in a digital building logbook.

[4] As a requirement of the European norm EN 15804+A2.

A wider usage of digital building logbooks and circular design would allow buildings to become ‘material banks’, a sort of material passport. Material passports store construction product data specifically relevant for disassembly, recycling, and disposal. This is illustrated by the Building as Material Banks project, which aims to reduce virgin material use, reduce waste and support a circular economy. Existing initiatives like Madaster have already developed digital material passports and are constantly improving their data quality.

When material passports storing data on reusability and detachability of materials become more mainstream, digital building logbooks would be ideal for storing this data and easily transferring it to the relevant value chain actors. This information could allow architects in the future to assess secondary construction materials available in their region and make it easier for these materials to be used when buildings reach their end of life. Logging the materials used in BIM during the design and storing these in material passports and digital building logbooks helps optimise the WLC performance of industrial prefabricated renovation solutions.

RESOURCE EFFICIENCY

Industrial prefabrication also has the potential to increase resource efficiency by reducing waste streams and minimising emissions related to the transport of building materials and products. Transport and waste generation are relevant when considering the WLC emissions of renovation projects.

Transport

Transport of industrially prefabricated renovation solutions differs from conventional construction transport because complete building parts or modules are transported rather than single construction components. Transport to the construction site is critical financially and environmentally for prefabricated construction solutions; the transport type, frequency and distance all influence the design of the modules that must be transported. Larger modules are more difficult to transport and might result in higher costs, whereas smaller panels allow a higher floor area to be transported at a time [19].

Transport needs should be incorporated into the design phase of the project: for example, designing modules that are small enough to transport on an average road will avoid complications and the need for alternative routes and longer transport times. Ensuring that trucks are at full capacity and building components are designed in a “packable” way so multiple modules can be moved at once will also reduce WLC. Finally, the material properties of the prefabricated solutions can affect transport-related emissions: for certain materials, like concrete, premanufacturing can increase, rather than decrease, the transport energy requirements [18].

Construction materials

Construction materials are often seen as the central component to reduce embodied emissions, including in the context of industrial prefabrication. To optimise the WLC performance, it is important to look at the quantity and type of construction materials used in the prefabrication process.

Quantity of materials

Construction waste can be significantly reduced by using industrial prefabricated methods. The controlled factory environment of industrial prefabrication, as well as the detailed pre-design coordination, can reduce excess construction materials and prevent waste. For new construction, material costs can be 5-10% lower on average for industrial prefabrication [4]. In addition, industrially prefabricated buildings often involve different construction materials. The design of the solutions is important because industrial prefabrication does not automatically lead to lower material use. If the design is not optimised for resource efficiency, a wooden prefabricated building can even lead to increased construction material use and waste compared to a conventionally constructed wooden building – though the weight of construction waste generated is still much lower than for other conventional construction materials such as steel and concrete. Standardisation and economies of scale are important for ensuring waste reduction [21].

Type of materials

Prefabrication using low-carbon materials in place of conventional construction materials such as concrete and steel can be a strategy to optimise WLC. However, materials and solutions should be fit for purpose, and properties such as lifespan and durability are also important. WLC should be considered in selecting what materials are used, especially given what is available regionally.

Industrial prefabrication has shown potential to optimise WLC performance of conventional construction materials like steel and concrete, as illustrated by a research project analysing the impact of prefabricated renovation solutions in Sweden, Spain and the Netherlands. Researchers assessed how reuse and recycling affected the energy, carbon and financial performance of precast concrete façade. Although the financial performance was not good, prefabricating and reusing the elements significantly improved carbon and energy payback times [22]. Similar studies in South Korea show that prefabrication of relocatable buildings with steel has the potential to reduce the embodied emissions up to the in-use phase significantly [23].

A case study of industrially prefabricated renovations for a multi-family building in Porto (the MoreConnect project) illustrates that the choice of materials proved to be crucial for the embodied emissions of the renovation. In this case, the choice for polyurethane foam for insulation negatively affected the overall environmental performance of the prefabricated renovation solution. The researchers reported two learnings from the project: first, to check the type of materials used (in this case for insulation) and second, to keep in mind the different lifecycles of products that are integrated into the panels in light of circularity [24].

QUALITY ASSURANCE

An important advantage of prefabricated construction over conventional renovation is quality control. Quality control is easier in a factory environment compared to the construction site, which has potential impacts on rework (redoing the work when something goes wrong) [4]. Reducing reworks can reduce construction time, costs and waste.

Another advantage is that the construction is not affected by outdoor weather conditions in the factory. For example, conventional construction seeks to waterproof a structure as quickly as possible, because precipitation can damage the structure and reduce the quality. This does not apply to industrial prefabrication, which has potential to improve the quality of renovation works. Producing in factories also allows for more standardisation and quality control, reducing the risk of not noticing expensive flaws in the design that must be repaired afterwards. A prerequisite is that the quality of the construction materials is higher, which might drive up costs [4].

All in all, better quality assurance has potential to improve WLC performance of industrial prefabricated renovation solutions, because higher quality can extend the lifetime of the building parts.

LIFECYCLE COSTING AND CIRCULAR BUSINESS MODELS

Considering the whole lifecycle to assess WLC has potential economic benefits and can function as a starting point for developing new circular business models for construction and renovation. One of the key promises of industrial prefabrication, despite the absence of a proven track record, is the delivery of cost savings and lifecycle cost benefits. This is where lifecycle costing can support finding affordable, WLC-optimised renovation solutions, for example by using circular business model strategies described below.

Lifecycle costing

Lifecycle costing considers the complete lifecycle of a measure, integrating the costs of operation and maintenance during the lifetime of measures besides the investment costs. Mapping the different lifecycle phases of a building or renovation measure and assessing the longevity of construction products and building installations enables building designers to better assess the construction and maintenance costs. This applies to conventional as well as industrial prefabricated construction and renovations. Industrially prefabricated renovations can reduce lifecycle costs if previously mentioned aspects like design and data storage, resource efficiency and quality assurance are achieved.

By also integrating the costs of operation during the building's lifetime, initial costs are balanced against future cost savings. Comparing the lifecycle costs of different scenarios is a valuable method to find cost barriers and changes and develop pricing strategies. Lifecycle costing strategies can also be combined with assessing the level of circularity, to find strategies that increase circularity without significantly increasing the lifecycle costs of the renovation, contributing to its affordability.

Case studies indicate that circularity can be increased significantly without raising lifecycle costs [25]. Moreover, energy system costs can be integrated into the energy price for different energy carriers, allowing for better modelling of affordability of different energy installations applied during a renovation [26].

Circular business models

Circularity and WLC impact are interrelated but different concepts. Circularity entails extending product lifetimes, reusing materials and reducing waste via repurposing and recycling. Circularity therefore influences the WLC impact of products and materials, but it is important to keep in mind that increased circularity does not automatically mean that WLC emissions are necessarily lower.

Compared to conventional construction, the potential for circularity is higher for industrial prefabrication in terms of reuse and refurbishment, upcycling and products-as-a-service [27]. Product-as-a-service entails that the manufacturer remains the owner of a product, and rather than selling the product to the user, it sells the service that a product provides. This encourages design for longer product lifetimes and predictive maintenance of products and building installations. Industrial prefabricated solutions could potentially reduce the amount of products, and stimulate the provision of "services" based on performance guarantees.[5] For example, Dutch industrially prefabricated net-zero renovations can be combined with a performance guarantee, whereby the building owner requests a construction company to deliver a renovation with a specified performance over longer periods of time [28].

Industrial prefabrication has circular potential: it can increase flexibility and longevity of products and support reuse of renovation solutions and installations. Complementary strategies are the elimination of redundant work and movements through material passports, take-back concepts, and taking responsibility for deconstruction and end-of-life treatment of construction materials [30]. Although barriers remain related to profitability and lack of capacity, industrial prefabrication has potential to further reduce embodied emissions when circular economy business models are applied.

Other studies indicate several strategies for applying circularity to prefabricated buildings or elements. Examples include lean production chains, reusing materials and designing for disassembly [30], as well as circular input materials, sharing platforms and resource recovery [31]. Such strategies also link to sufficiency policies for the building sector, an often-neglected aspect of energy policy that aims to define sufficiency levels e.g. for space usage, construction design, building equipment and use. Designing spaces for multi-functionality, extending the lifetime of existing buildings and designing for deconstruction are all aspects that can be fostered by industrial prefabrication of renovation solutions [30]. These links with circular business models deserve further analysis and have potential to improve the WLC performance of industrial prefabricated renovation solutions.

[5] In the Netherlands some providers of NOM (net-zero) renovations offer energy performance guarantees over periods ranging from 7-25 years, in which the solution provider can take responsibility for monitoring and maintenance.

EXISTING STUDIES ON WLC REDUCTIONS IN PREFABRICATED BUILDINGS

Case studies show that there is clear potential to reduce embodied emissions through industrial prefabrication for new buildings (see Annex 1). This invites us to implement similar approaches for renovations. However, we need more comparative LCA studies comparing industrial prefabricated renovation solutions with conventional renovation solutions. Prefabrication, in itself, is not sufficient to reduce embodied emissions, even though it can improve performance and is applicable to a wide range of construction materials including steel, concrete and wood. Certain construction materials tend to have lower WLC impact and a reduced "carbon spike" (large quantity of emissions during construction) compared to others. The choice of construction materials and their properties is therefore essential to reduce the embodied emissions over the lifecycle, like product and building design anticipating reuse at end of life. In all design scenarios, different lifecycles of construction products should be kept in mind to make sure that maintenance and repair is possible, and no resources are wasted.

Key opportunities to enhance WLC in industrial prefabrication of renovation solutions:[6]

- Design is the cornerstone to improving the WLC performance, for example through design for reuse, and is positively affected by increased use of BIM and digital building logbooks and integration of reliable environmental data.
- There is clear potential to significantly improve resource efficiency, for example through higher design accuracy and waste reduction.
- Means of transport and factory site location must be carefully selected to achieve significant overall embodied emissions reductions.
- Quality assurance is usually higher in off-site manufacturing.
- Lifecycle costing, the economic equivalent of lifecycle assessment for carbon and other environmental impacts, helps identify cost-effective strategies based on the complete lifecycle of the investment.
- Industrial prefabrication has circularity potential and can be linked to several circular strategies like product-as-a-service or design for disassembly.

[6] For further information on the case studies see Annex I.

POLICIES TO DRIVE THE UPTAKE OF INDUSTRIAL PREFABRICATION AND WLC

The policies for both industrial prefabrication and WLC are still being developed within the EU.[7] In the absence of clear EU regulations, Member States and local authorities are already developing WLC policies, for example in Denmark, Finland and the Netherlands.[8] As a result, significant geographical disparities in terms of WLC policy instruments exist. North-western European national authorities have initiated disclosure requirements and some have already started setting embodied emission ceilings for new construction, whereas other EU countries are lagging behind [33].

As mentioned, Member States are starting to create policy targeting WLC. Tailored policies focusing on the preconditions for industrial prefabrication and WLC reduction strategies for industrial prefab are important to create the necessary market to increase renovation rates while reducing emissions over the lifecycle. Policies should:

- Promote digitalisation of the renovation sector.
- Provide targeted financing for industrial prefabrication of renovation solutions.
- Foster WLC reduction strategies related to all lifecycle phases of a building, in particular design.
- Foster circular economy business models within the renovation sector such as design for disassembly, product as a service, sharing platforms, product take back and use of secondary materials.
- Strategically support start-ups focusing on innovative solutions for industrial prefabrication.

[7] The 2021 EPBD recast proposal includes WLC for the first time.
[8] For more information see: https://www.bpie.eu/wp-content/uploads/2021/05/BPIE_WLC_Summary-report_final.pdf.

ENERGY PERFORMANCE OF BUILDINGS DIRECTIVE AND CONSTRUCTION PRODUCTS REGULATION

Ongoing revisions to the EPBD and Construction Products Regulation offer opportunities to drive the uptake of WLC and industrial prefabrication of renovation solutions.

Energy Performance of Buildings Directive

The Energy Performance of Buildings Directive is key legislation to drive further WLC reductions in the European building and renovation sectors. In the 2021 recast EPBD proposal, WLC is mentioned particularly in relation to larger new buildings, as a first step to increasingly consider WLC performance of buildings and a circular economy.

Although the EPBD proposal states that WLC emissions of buildings must be progressively integrated in EU building policy, it lacks of ambition and vision.[9] Rather than just requiring disclosure of WLC emissions, the EPBD should define how WLC relates to zero-emission buildings and regulate such impacts to achieve WLC reductions for new buildings. Although the ambition and vision should be improved, it is welcome that the EPBD proposal stresses the importance of building design. It recognises the need for resource efficiency, circularity and requirements to calculate lifecycle global warming potential for new buildings, particularly when we envision buildings as temporary carbon sinks[10] [34]. It however does not yet apply to renovations or existing buildings, which should be considered to decarbonise the building stock.

WLC should be better be integrated into the EPBD, and further implementation efforts are needed to fully align the EPBD proposal with the ambition expressed in the Fit for 55 and 2050 climate targets. Specifically, the national building renovation plans (formerly national long-term renovation strategies) have great potential to trigger WLC reduction strategies and establish the preconditions for industrial prefabrication of renovation solutions.

[9] See the BPIE (2022) EPBD Policy Briefing for a more in-depth analysis.

[10] There is discussion about the potential of construction materials absorbing carbon from the atmosphere and to store this carbon (temporarily) in buildings. For more info see [39].

The EPBD proposal should include the following:

- Member States should include milestones towards 2050 in their national building renovation plans to ensure the building stock stays within the allocated carbon budget while taking into consideration WLC impacts.
- The EU should consider establishing an EU-wide methodology for the calculation of WLC emissions of complete buildings or support comparability of calculation methods so that Member States can establish national targets and benchmarks in a uniform, comparable way.
- In their national building renovation plans, Member States should identify neighbourhoods and districts suitable for industrial prefabrication renovation solutions and report identified areas periodically, including progress on industrial prefabrication implementation.
- Member States should encourage industrial prefabricated renovation solutions that explicitly incorporate whole-life carbon emissions reduction strategies to achieve deep (zero-emission building) renovations beyond 2030.
- Member States should be required to quickly update their regulatory framework to ease and speed up permitting and tendering procedures and report progress in their national building renovation plans (e.g., for multi-family buildings and homeowner associations), as well as to support companies active in the sector, for example through tax breaks.

In general, the EPBD should be aligned with parallel EU policy initiatives like the 2050 whole-life carbon roadmap, the sustainable products initiative and green public procurement. This requires either a specific mention of WLC in the directive, or accompanying support such as Member State guidance or directive annexes to align directives and initiatives.

Construction Products Regulation

Besides the EPBD there are also opportunities to foster WLC reductions within industrial prefabrication related to the 2022 proposal for the Construction Products Regulation. Embodied carbon and the environmental performance of building materials could have a direct impact on the overall whole-life carbon footprint of industrial prefabrication renovations, therefore there is room to improve the current proposal, in particular by:

- Mandating obligatory common EU product category rules for EPDs.
- Preparing and establishing a single EU carbon and LCA impact database underlying EPDs.
- Making EPDs mandatory for all construction products – in the current proposal of the European Commission this is not the case. Making EPDs mandatory for communicating environmental/carbon information about construction products could give a boost to data gathering.
- Creating a framework for repurposing used construction products.
- Requiring manufacturers to design products in a way that facilitates reuse, remanufacturing and recycling, through separation of components and materials.
- Providing a clear timeline or workplan for the development of minimum requirements per product category, restricting access to market and phasing out the worst-performing products.
- Requiring digital product passports for construction products as per all other products under the Sustainable Products Initiative.

FUNDING AS A DRIVER FOR INDUSTRIAL PREFABRICATION MEASURES

To incentivise industrial prefabrication with increased consideration for WLC reductions, the Commission and Member States should establish dedicated funding streams that require a specified level of emissions reductions. For example, the German Federal Ministry of Economic Affairs is supporting industrial prefabrication of renovation solutions through a grant programme focusing on feasibility studies, pilot projects and investment support. Additional support from regional and national governments to foster financing for industrial prefabrication of renovations could:

- Support companies active in the market for industrial prefabrication through tax breaks.
- Update regulatory frameworks to ease and accelerate permitting and tendering procedures.
- Incorporate quality standards and guarantees into supply agreements for industrial prefabrication.
- Establish quality standards and/or a fund for performance guarantees related to industrial prefabrication and WLC performance for industrial prefabricated (renovation) solution providers.

POLICY MEASURES ARE CRITICAL TO FOSTER OTHER DIGITAL SOLUTIONS

Digitalisation is essential to substantially increase innovation in the building sector while enabling deeper energy gains and emissions reductions. Policymakers should therefore encourage the use of digital solutions, especially BIM, for example in public procurement processes or through building codes to foster WLC disclosure and pave the road for future WLC regulation and industrial prefab dissemination [9] [35].

A prerequisite for effective policies is the quality and validity of the environmental data used in digital tools. Policymakers should therefore harmonise EPD methodologies and the underlying environmental data. They should also foster research into end-of-life scenarios for low-carbon materials and integrate this into regulations, similar to the obligatory reporting for EPDs. In addition, a Europe-wide digital building logbook should be adopted in order to store and compare building data throughout the lifecycle of the building.

Conclusions

In order to reach EU targets, reduce emissions and future-proof the EU building stock, innovative solutions are needed to renovate existing buildings. Industrial prefabrication for renovation is one emerging solution to help quickly meet EU renovation targets and lower energy consumption. Putting in place effective mechanisms to reduce WLC emissions may implicitly help to boost industrial prefabrication and vice versa.

KEY STRATEGIES TO REDUCE THE WLC IMPACT OF INDUSTRIALLY PREFABRICATED RENOVATION SOLUTIONS ARE DESIGN, RESOURCE EFFICIENCY, QUALITY ASSURANCE, LIFECYCLE COSTING AND CIRCULAR BUSINESS MODELS. THE EU SHOULD LEVERAGE BUILDING POLICY TOOLS IN THE EPBD AND CONSTRUCTION PRODUCTS REGULATION AND FOSTER DIGITAL TOOLS LIKE BIM, DIGITAL BUILDING LOGBOOKS AND QUALITY ENVIRONMENTAL DATA TO ENSURE EUROPE MEETS THE FIT FOR 55 TARGETS AND THE RENOVATION WAVE.

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ANNEX I

Case studies comparing WLC emissions of new prefabricated and conventional buildings in europe

Research linking WLC to industrial prefabrication is still relatively rare, but existing cases provide insights into opportunities and considerations that should be integrated in policies and other efforts aimed at increasing the uptake of industrial prefabrication and WLC.

Ideally the analysis in this section would focus on the embodied emissions of renovations, but due to a lack of comparative studies the case studies focus on embodied emissions of new residential buildings in the EU. The results cannot be translated exactly to the renovation sector due to the higher complexity of working with existing buildings and the technical, financial and social particularities related to renovations. Despite these limitations, these case studies do shed light on the relevance of WLC assessments for industrial renovation. If part of these benefits applies to renovations, this would suggest industrial prefabrication has potential to reduce WLC emissions of renovations compared to conventional renovation methods.

The Bertim Project – prefabricated renovation modules

The Bertim Project developed and implemented wooden prefabricated solutions based on laser scanning and BIM technology. The wooden design was chosen to reduce the primary energy demand of the materials from cradle to grave and performs well on indicators such as global warming potential, solid waste and embodied energy [39]. The materials are also easily recyclable, further adding to the circularity potential of the building components.

Bertim is a project financed by Horizon 2020 with the aim of improving the competitiveness of wood construction in energy retrofits of residential buildings. The project was led by 12 European partners including three wood construction manufacturers: EGOIN in Spain, POBI in France and SETRA in Sweden. The Bertim project introduced a digitalised renovation methodology, from the collection of building data and its subsequent processing into BIM format, to the installation of prefabricated modules, which significantly improved the efficiency and precision of the construction process.

To guarantee the quick and affordable installation of prefabricated modules, the University of Munich designed an anchoring system that overcomes the irregularities of the existing façade and allows highly efficient placement. Overall, the Bertim project developed an effective way to make use of innovative timber prefabricated modules in accelerating and streamlining energy renovation in various geographical and climatic conditions across Europe [37].

New prefabricated versus conventional construction: Comparing lifecycle impacts of alternative structural materials

The choice of structural materials of buildings is an important contributor to the WLC performance. A study by Taveres and colleagues from May 2021 compares prefabricated timber and hybrid timber-steel frame single-family buildings with conventionally constructed reinforced concrete and double brick outer wall residential buildings. The outcome shows that through prefabrication and different structural materials, opportunities exist to reduce embodied carbon by up to 60%. Prefabrication generates up to 80% less construction waste, while end-of-life considerations are also important.

The prefabricated wooden frame and wooden/steel hybrid have significantly fewer impacts, due to the type of materials but also because of the dry disassembly system allowing better waste separation at end of life [38]. There were also significant differences between the wooden frame and the steel/timber frame, showing that the choice of structural materials is essential to reduce embodied impacts. The steel/timber frame building had 50% higher impacts, for example. Similar differences applied with the conventional designs, with the concrete block wall house's impacts being more than one-third higher than the double-layered brick wall design. This illustrates that regulating WLC of buildings will influence the choice of structural materials.

The study also shows that the design choice is important. Changing the ratio of the size of the external walls to gross floor area would have significant impact on the weight of materials used. Moreover, the study assessed the time reductions that can be achieved by prefabrication and stressed that prices for wood and steel are high compared to those of the large-scale conventional materials like bricks and concrete. The study concludes that prefabricated houses from timber and steel can be produced for similar prices as conventional buildings while producing less waste, using less materials and having similar functionality.

Comparison of new built prefab houses in different climates

Prefabrication has the potential to significantly lower the embodied impacts of new buildings, but to ensure that changes in operational energy consumption do not diminish these benefits, Taveres and Freire performed a complete LCA on a lightweight prefabricated residential building.

This paper gives an LCA of a single bedroom steel frame timber residential building constructed through prefabrication. The design is adopted in terms of insulation levels to seven sites located in three climate zones (continental Europe, Mediterranean Europe and tropical) and corresponding electricity mixes. The authors also compared the lifecycle impacts of three insulation levels (PVC with Rockwool infilling and polyurethane insulation) and two heat pump systems with different efficiency ratios in these seven locations (resulting in 42 alternative scenarios).

The system boundaries of the study are from material extraction to the use phase (50 years). The end-of-life phase was left out of the analysis due to expected low lifecycle impact (1-6%). These are caused by the better capacity of prefabricated buildings to be disassembled, and higher waste recovery rates. These would contribute to better performance of the prefabricated buildings compared to conventional construction [39].

A BIM model was used to forecast operational energy use and to generate a “material bill”, containing the construction materials used. The Level(s) framework and EN 15978 standard[11] recommendations were used to select eight impact categories for the LCA.

The use stage had the largest overall lifecycle impact, followed by the embodied impact of the materials used. During the use phase, the heat pump systems and other appliances have the largest overall impact. One learning is that the insulation level should be adjusted to the climate: higher insulation in warm climates increases the operational impacts due to increased cooling needs. This illustrates on the one hand that decarbonising the electricity mix is essential, and also that local climatic conditions should be factored into the design to achieve WLC impact reduction.

Key takeaways and case studies

- There is clear potential to reduce embodied emissions through industrial prefabrication for new buildings. This invites us to implement similar studies for renovations.
- We need more comparative LCA studies comparing industrial prefabricated renovation solutions with conventional renovation solutions.
- Prefabrication in itself is not sufficient to reduce embodied emissions, even though it can improve performance and is applicable to a wide range of construction materials including steel, concrete and wood.
- The choice of construction materials and their properties is essential to reduce the embodied emissions over the lifecycle, as are product and building design anticipating reuse at end of life.
- Different lifecycles of construction products should be kept in mind to make sure that maintenance and repair is possible and no resources are wasted.

[11] The EU standard for the assessment of environmental performance of complete buildings, through LCA.

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