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CIRCULAR ECONOMY PRINCIPLES IN INNOVATIVE FACADE APPLICATIONS: A REVIEW OF FIBRE-REINFORCED PULTRUDED PROFILES APPLICATIONS FOR ENERGY-EFFICIENT BUILDINGS

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ABSTRACT

Background and aim. Addressing resources and energy efficiency within the construction sector is the key to achieve the EU's ambition of climate neutrality and fully decarbonised of building stock by 2050. This paper explores the integration of circular economy principles, with a specific focus on fibre reinforced pultruded profiles as a sustainable material. It provides an overview of the characteristics and manufacturing processes of continuous pultruded profiles, exploring their potential implementation in facade components, and conducts a theoretical comprehensive sustainability assessment of their environmental impact. These materials contribute to potentially increase the environmental sustainability of the construction sector, reducing the overall lifecycle expenses, and boosting the energy performance of buildings.

Methods and data. A mixed-methods research design was employed, combining a comprehensive literature review and analysis of case studies. These methods evaluated the characteristics, manufacturing processes, and environmental performance of fibre-reinforced pultruded profiles in facade applications.

Findings. The research highlights key technologies that can increase resource efficiency and reduce waste in the fibre reinforced polymer industry. Prospects for technological advances in pultrusion processes are discussed. The findings reveal that pultruded composite materials offer significant advantages, including resource efficiency, waste reduction, and improved energy performance of building skins for durable and low-maintenance facade systems.

Theoretical / Practical / Societal implications. Practically, this research highlights the potential of pultruded profiles for innovative facade design by incorporating circular economy principles. Societally, the findings support the transition to sustainable building practices, contributing to climate goals and resource conservation. This theoretical interdisciplinary approach addresses the challenges of modern façades systems and lays the groundwork for sustainable, energy-efficient buildings.

KEYWORDS: Circular economy, Facade application, Glass fibres, Pultrusion, Recyclable, Sustainability

1 INTRODUCTION

In March 2020, the European Commission presented the circular economy action plan, which aims to promote more sustainable product design, reduce waste and empower consumers (Circular Economy Action Plan For a cleaner and more competitive Europe, European Commission 2020_98_final report). Energy efficiency and sustainability in the building sector are necessary to achieve the 2030 Agenda for Sustainable Development Goals (General Assembly, 2015, the 2030 Agenda for Sustainable Development). The construction industry is one of the major responsible of climate change and global waste production (Pastori et al., 2021).

Heating and cooling in buildings and industry account for 50% of the European Union's energy consumption (Towards a smart, efficient and sustainable heating and cooling sector, European Commission. 2016_final report). Governments, companies, and consumers each have a crucial role when transitioning from a linear to a circular model of production and consumption. However, the circular economy is not only focused on technical

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aspects. The approach involves the complete value chain, from product design and production processes to consumption and waste management. The regeneration process become a valuable resource. To fulfil this ambition, the EU needs to accelerate the transition towards a regenerative growth model that gives back to the planet more than it takes, advance towards keeping its resource consumption within planetary boundaries, and therefore strive to reduce its consumption footprint and double its circular material use rate in the coming decade (Circular Economy Action Plan For a cleaner and more competitive Europe, European Commission 2020_98_Annex). The transition to a circular economy goes hand in hand with new legislative framework, new business models, standardisation, green public procurement, and a new design thinking that takes into account reparability, durability, and recyclability (Mrotzek-Blöß et al., 2019). The key point is replacing virgin raw materials with recycled raw materials.

Literature suggests that implementing circular economy strategies can help mitigate impact reduce carbon emissions and improve sustainability in construction practices. However, while existing studies have addressed the potential of circular practices, there is a gap in understanding how these strategies can be specifically applied to the lifecycle of Fibre-Reinforced Polymer (FRP) materials in building façade applications. In the following paragraph the research focuses on possible strategies for new application of FRP in building façades components represent one of the key to the building systems integration necessary to realise critical health, carbon, resilience, and sustainability goals in buildings and urban habitats (Boswell et al., 2021).

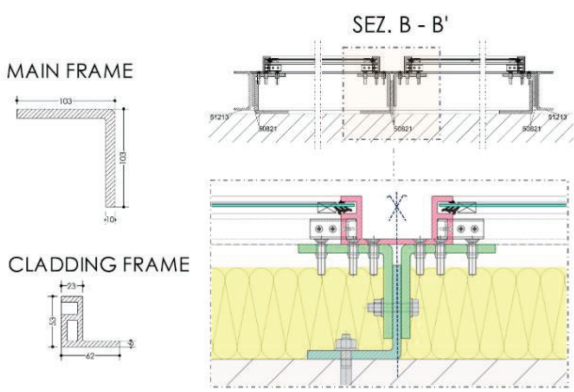

Figure 1: Schematic representation of the ventilated façade system and its components – system design

The components of the innovative façade system (see Figure 1) include a combination of mullion profiles and brackets, both made of pultruded composite material. The substructure consists solely of vertical elements, which are connected to the support using a bracket system that allows for the adjustment of installation tolerances on-site. The cladding consists of cassette panels made of composite material as well, with an infill photovoltaic glass unit. The use of fibre-reinforced polymer (FRP) leverages its advantageous properties, including high mechanical performance, favourable thermal behaviour, fire and weather resistance, and durability. To ensure that buildings are fit for the EU's enhanced climate ambition under the European Green Deal, the revised directive will contribute to the objective of achieving climate neutrality by 2050 (European Commission, Fact Sheet, 2016. *Energy Performance of Buildings Directive, European Commission*). The drivers of climate change and biodiversity loss are global and are not limited by national borders (The European Green Deal*,* European Commission, 2019_640_final report). The paper is divided into five sections. Section two explores the phases of the pultrusion process and discusses material characteristics in the case study. Section three is related to the methods and provides an overview of the main sustainability regulations and guidelines. Section four addresses the main strategies and current approach for disposing of composite materials. The final section five, highlights the potential of pultrusion technology and outlines future prospects related to a circular economy framework concerning FRP composite materials.

2 CASE STUDY: PULTRUDED PROFILES DEFINITION, MANUFACTURING PROCESS AND CHARACTERISTICS

Compared to traditional manufacturing processes that may involve energy-intensive procedures, pultrusion stands out as a sustainable alternative. The process allows for precise control over material composition and results in profiles with consistent quality and performance. Pultruded profiles offer an innovative solution that surpasses conventional materials in terms of durability and design flexibility.

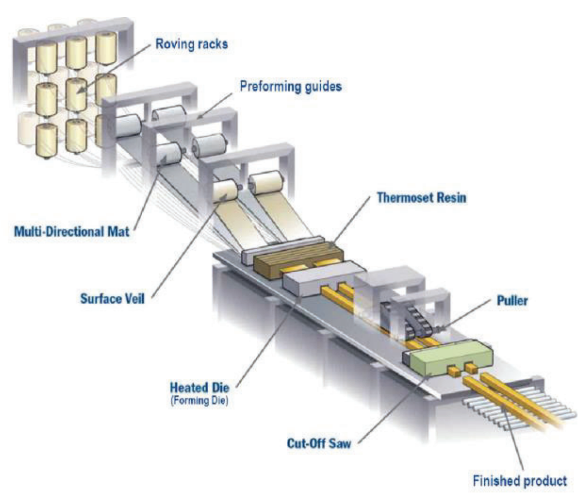

Figure 1: Right: Manufacturing process scheme - source adapted by the author from [Bedford reinforced plastics, Inc.]

FRP components are characterized by limited maintenance than traditional building materials such as wood, steel or aluminium. As a consequence, pultruded profiles align with circular economy principles by optimizing resource use, minimizing waste, and reducing the environmental impact associated with material production (figure 2). Specifically, the process uses matrix and fibres for the manufacturing of composite standard profile or custom parts for very specific needs (figure 3). Common materials used in the reinforced phase are glass, polymers, metals, ceramics, and graphite, which provides easy compatibility with matrix polymers at low cost. Thermosets and thermoplastics are the most commonly used polymers in the manufacturing of composite materials. This method involves the pulling of reinforcing fibres through a resin bath, ensuring uniform distribution, and subsequent curing to form a robust and versatile composite material (figure 4).

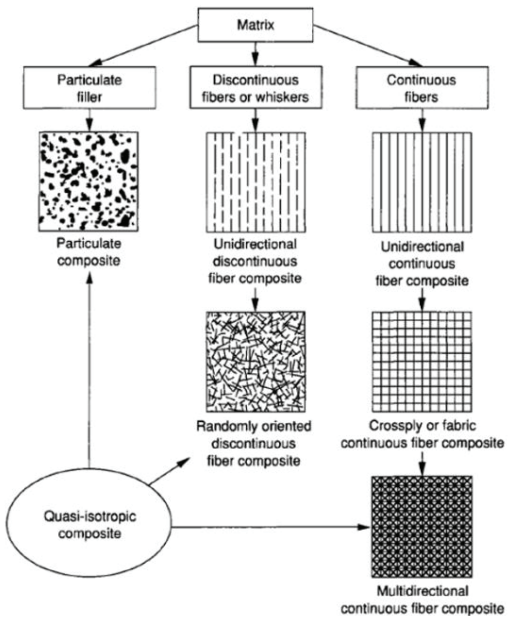

Figure 2: Classification of composite material systems – source [Ishai O, 2018]

The key properties responsible for the rising demand for pultruded composites include excellent tensile strength, high chemical resistance, non-magnetic properties, low thermal expansion and low maintenance. From a technical point of view, they are not comparable to other traditional materials but these materials are still little used in construction field due to a lack of knowledge on the part of designers. Pultrusion is an automated technological process that creates high-quality composite profiles with a consistent cross-section. This is achieved through the impregnation of fibres with resin and their passage through a heated die (Nguyen et al., 2013). Subsequent to impregnation, the profile is shaped using a heated die, ensuring proper curing and solidification.


Figure 3: Right: Pultrusion process, roving racks, preforming guides, roving, surfacing mat – source [Italcomposites Doo]

The characterization in the other two directions is mainly given by the thermoset resin selected. Over time the process evolved and, as first improvement, it was possible to die along with the longitudinal fibre also layers of mat or fabric in 1960s; later in 1970s (Barkanov et al., 2022). Fibre-Reinforced Polymer profiles, engineered through pultrusion, have proven their versatility in diverse architectural elements, ranging from cladding panels to load-bearing structures. The inherent characteristics of pultruded profiles make them particularly well-suited for sustainable construction practices. Notably, their high strength-to-weight ratio imparts structural integrity without excessive material consumption.

The material's non-conductive properties contribute to improved energy efficiency in building applications. Moreover, the application of FRP pultruded profiles in façade components contribute in a reduction in the overall weight of the facade, contributing to a more efficient and cost-effective construction process. These positive outcomes underscore the practical advantages of pultruded profiles in real-world construction scenarios, aligning with the principles of circular economy by promoting resource efficiency and waste reduction. FRP composites have also a good ratio between price and low level of embodied energy which also means that the energy required to manufacture the component is markedly lower than in the case of a metal assembly (Knippers et al., 2011). Additionally, the versatility of pultruded profiles allows for customization to diverse design requirements in facade geometry.

Figure 5 utilizes different colors to distinguish between various materials. Gray circles represent the baseline or reference group, while colored circles correspond to specific materials such as pultruded FRP, extruded aluminum, etc. The comparison shown in the graph represents the price-to-embodied energy ratio for standard profile dimensions up to a maximum of 150 x 100 mm (this size can generally be considered a good average dimension for the type of façade application discussed in the paper). The analysis presented in the graph takes into consideration the embodied energy for the primary production of metal-based and composite-based materials (X-axis), with the prices per unit mass shown on the Y-axis.

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3 METHODS: OVERVIEW OF THE MAIN SUSTAINABILITY ASPECTS AND REGULATIONS

A United Nations projection (A/RES/70/1) estimates that the world's population will reach 9.7 billion by 2050 and 10.4 billion in 2100. An estimated 70% of these people will live in cities, up from 54% today. This growth involves gigantic challenges in term of infrastructure, energy and the environment. Huge new investments will be required and the use of sustainable building techniques and new building materials will be essential. The Ance Study Centre (Italian Association of Building Manufacturers) estimated that approximately 430,000 energy efficiency interventions will be necessary (JEC composites magazine, 2024, Composite material in civil engineering and architecture, n. 154).

The European market (figure 6) for glass-reinforced polymers has experienced a steady yearly growth of + 2% since 2009. Pultrusion was the fastest growing, with a pultrusion market valued at €1.87 billion in 2020, which is expected to grow by €2.98 billion by 2028 (Elmar et al., 2018). Current practices, especially in the construction sector, are mainly oriented towards waste management and recycling, which is the least optimized solution in the hierarchy of circular actions, but also the most promoted by the current European legislative framework.

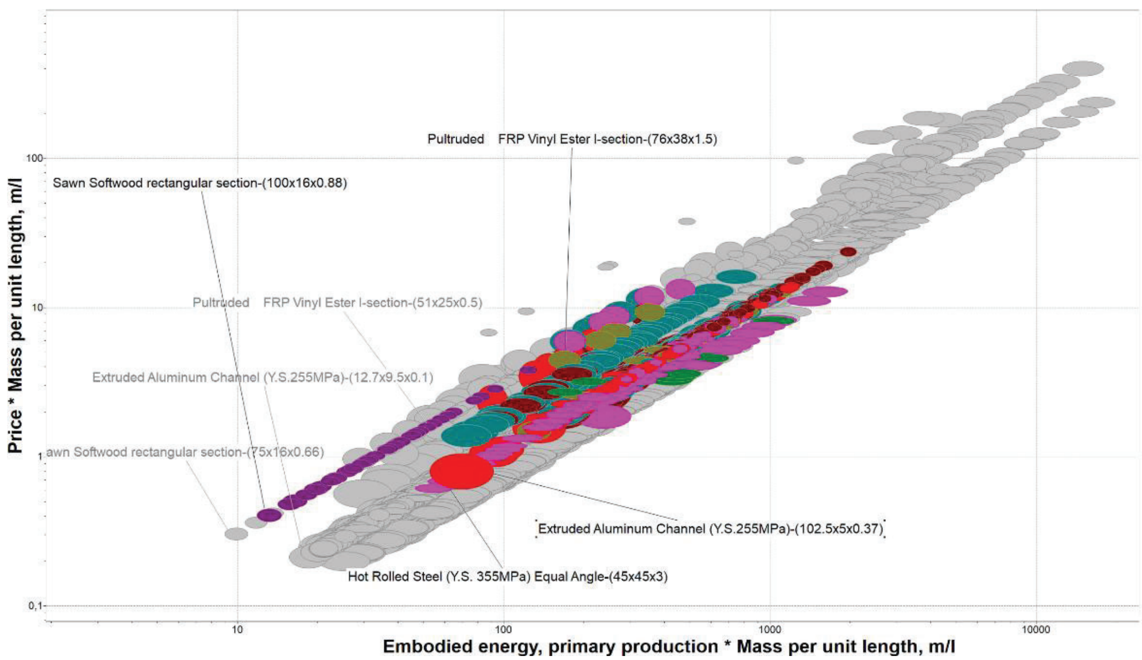

Figure 5: Comparison of Price vs. Embodied Energy: FRP vs. Traditional Materials (Profiles up to 150 x 100 mm) – Analysis calculated using Granta ANSYS Software.

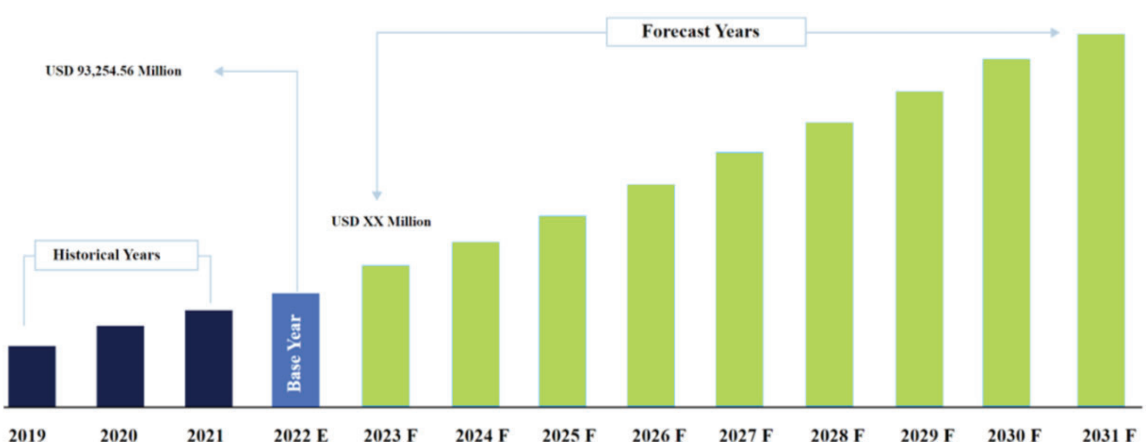

Figure 6: Fibre-Reinforced Composites market size, demand over the years - Study Period 2018-30 (Report Code SRCH1729DR) - source adapted by the author from [Straits, 2024]

Moreover, downcycling activities, such as the reuse of aggregates for the construction of road foundations, deriving from the need to solve the problem of managing construction and demolition waste at the end of the building service life, are the most practiced (Lavagna et al., 2022). A detailed analysis of the current regulatory framework was conducted to understand how existing sustainability strategies align with European and global policies. the study examined how the circular economy principles, waste management regulations, and recycling technologies impact the use of pultruded fibre-reinforced polymer materials. The research also evaluated the implementation of the waste hierarchy in FRP production and end-of-life scenarios, highlighting the need for more efficient and sustainable practices.

Circular economy (figure 7) means an economic system whereby the value of products, materials and other resources in the economy is maintained for as long as possible, enhancing their efficient use in production and consumption, thereby reducing the environmental impact of their use, minimising waste and the release of hazardous substances at all stages of their life cycle, including through the application of the waste hierarchy (Regulation (EU) 2020/852). A more circular economy increases the life-span of products increasing reuse, reparability, durability, upgradability and promoting innovative forms of consumption such as the collaborative economy (European Commission, SWD 306 final, 2023).

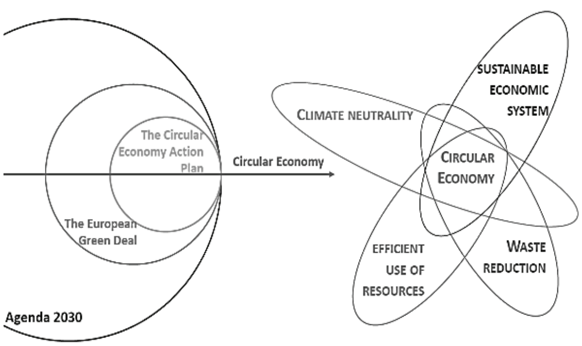

Figure 7: The multiple values of circular economy – source adapted by the author from [Dalla Valle et al., 2022]

Current trends reveal how remanufacturing is an activity implemented not only as an End-of-Life sustainable strategy but also during the whole life cycle of a product. In this scenario, the waste hierarchy is a framework that outlines the preferred approaches for managing waste in order of priority, with the goal of promoting sustainability and minimizing environmental impact.

Applying the waste hierarchy to pultruded profiles emphasizes the importance of sustainable practices throughout their life cycle, from production to end-of-life management. Incorporating specific sustainability metrics, such as energy consumption, CO_2 emissions (manufacturing, installation, etc), and material waste (quality), would provide measurable indicators to evaluate the effectiveness of these practices. By prioritizing prevention (minimize the generation of waste), promote recovery and recycling techniques, reduce pressure on resources and boost the transition to a circular economy (figure 8).

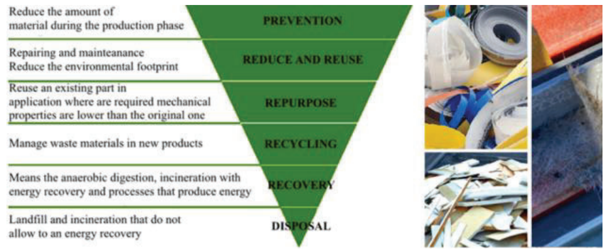

Figure 8: Waste management hierarchy as per The European Union's 2008/98/EC directive - source by the author from [De Fazio et al, 2023]

The waste management principles reduce the environmental footprint and contribute to a more circular and sustainable approach to the material use (minimises the incineration of waste and avoids the disposal of waste, including landfilling, in accordance with the principles of the waste hierarchy). FRP waste material negatively impacts the local environment by contaminating the soil, air, and groundwater. Landfill and incineration are not recycling methods. The incineration route still leaves behind 50% of the waste material as ash, which still needs to be landfilled (Jacob, 2011). Most FRP production waste ends up in a landfill. Dumping this waste in a landfill may not be the best sustainable waste disposal solution and commonly the space available in landfill sites may be limited in some countries.

The transformation, however, will not happen by itself, but important promotion actions need to be taken by various stakeholders, like policy-makers, industrial companies, research and academic community as well as the general public (Karvonen et al., 2017). Circular practices in the Fibre Reinforced Plastic (FRP) profiles industry are still emerging but gaining traction due to the growing awareness of sustainability and environmental concerns. Potential circular practices take in consideration the closed-loop manufacturing processes where waste materials generated during production are collected, recycled, and reintegrated into the manufacturing process.

This aspect reduces the reliance on new raw materials and minimizes the environmental impact of production (in Figure 9, the recycling loop illustrates the process from raw material to the machining phase, leading to the finished components. The loop also presents the potential end-of-use phase after utilization and disassembly. On the right side of Figure 9, the pultruded profiles are categorized under the group of continuous fibres with different orientations in a grid).

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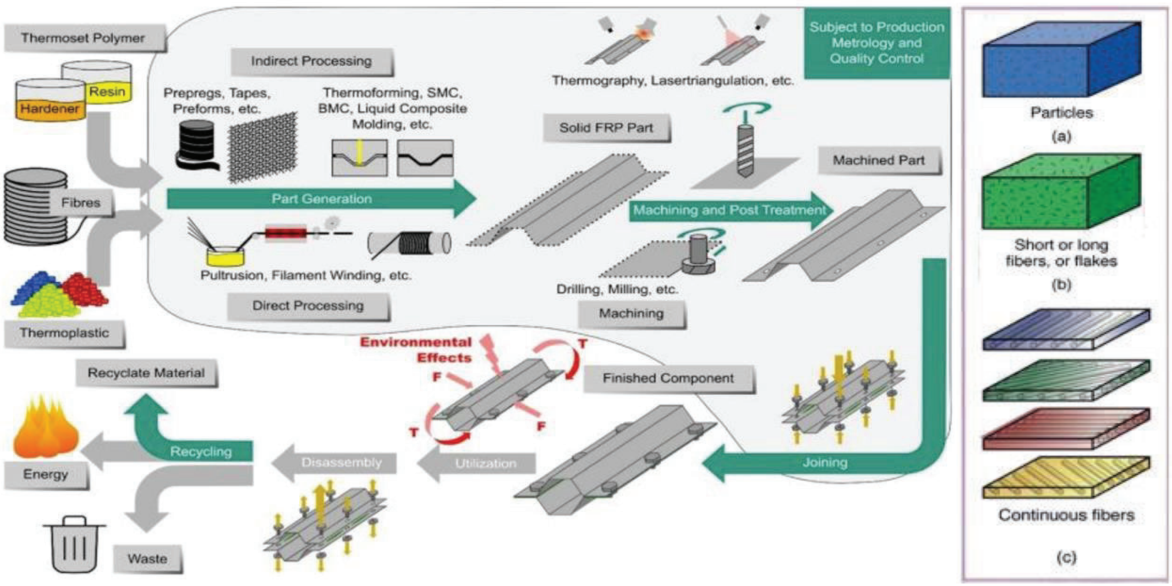

Figure 9: Methods of reinforcing plastics in particles (a), short fibres (b) and continuous fibres (c) – source adapted by the author from [UCIMU Association]

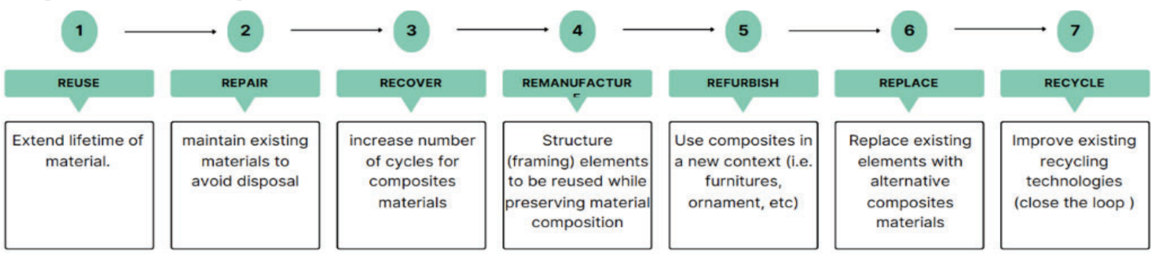

Figure 10: Circular thinking and the use of the 'R' strategies for composite material

The main critical and controversial Life Cycle Assessment issues concern the definition, on one hand, of the service life and, on the other, of the allocation procedures. Incorporating LCA parameters such as environmental impact, material flow analysis, and energy consumption throughout the life cycle of FRP components would provide a more rigorous framework for evaluating sustainability practices. Indeed, the potential for multiple life cycle is limited by the products reversibility and the number of use cycles strictly depends by the associated service life (Dalla Valle et al., 2022).

There are many options for extending the lifetime of composite components. For example, the product might be used as it is for the same purpose in a different application (reuse), or its use can be extended by applying conventional maintenance techniques both in situ (repair) and through industrial processes (refurbish and remanufacture). If repair is not possible, the product can often be used for a different function (repurpose). When these options are finally exhausted, recycling is possible through both closed loop and open loop processes (EuCIA Association, 2024). The EU policy on Construction Product Regulation (CPR) and its Basic Requirement of Construction Works (BRCW) 7 Sustainable use of natural resource could provide a good basis for optimizing resources, including reuse (Hobbs et al., 2017).

It is challenging but potentially very important to resolve Circular Economy in facades with a view to transitioning from the take–make–waste mindset to one of reduce–reuse–recycle. In other words, in order to approach a circular thinking regarding the difficult end-of-life opportunities of composite materials, many R-strategies (Chatziparaskeva et al., 2022) of circularity (e.g., reuse, reduce, recycle, refurbish, remanufacture, etc.) should be taken into account (figure 10). The wind industry in Europe is projected to generate approximately 15,000 tonnes of blade waste annually between 2020 and 2023 (data from Association WindEurope). This amount is expected to rise in the next years and exceed 60,000 tonnes annually by 2030 (figure 11). Following this information, the wind energy sector has more precise knowledge about the amounts of composite materials to be decommissioned each year (compared to the construction sector).

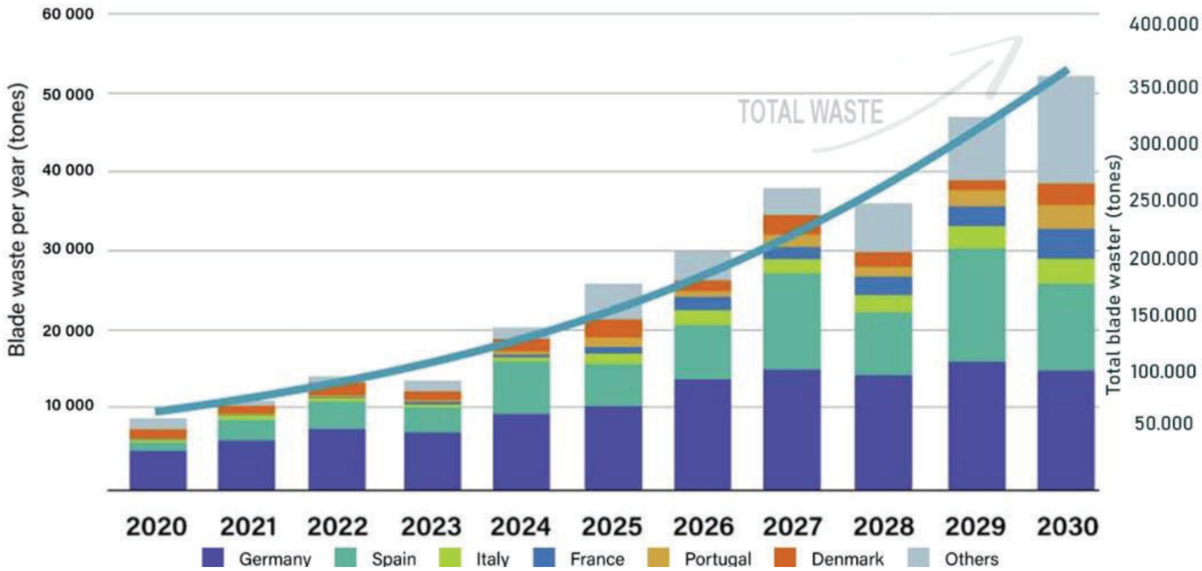

Figure 11: Decommissioned blade weight (including repowering) - source adapted by the author from [European Boating Industry AISBL, 2023]

This visibility on composite waste volumes makes the wind sector a prime mover in supporting the establishment of a business plan for the industrialisation of composite recycling/upcycling. Cement kiln co-processing, while costly, is the treatment technology that is already available and that could be increasingly used within the next years to transition to the circular economy approach. Glass fibre can be a source of silica that is needed in the cement production.

One ton of composite material leads to the saving of 460 kilograms of primary raw material (such as sand). Polymers can be used to produce energy. The high efficiency and lower CO_2 emission factor, reduces the total CO_2 impact of the cement production process. One ton of composite can save approximately 110 kilograms of CO_2 compared to fossil fuels (European Boating Industry AISBL, 2023).

4 RESULTS: STRATEGIES BASED ON PULTRUDED FIBRE-REINFORCED POLYMER MATERIAL

The circular economy model aims to optimize resource use, minimize waste, and promote sustainable practices throughout a product's life cycle. Applying this model to pultruded profiles involves understanding and managing material flows to enhance their environmental and economic sustainability.

Current methods of disposing composite materials involve mostly landfilling, cement clinker co-processing and recycling by matrix degradation. Co-Processing technique is the use of waste as raw material, as a source of energy, in industrial processes, such as cement, lime, steel, glass, and power generation (Vijay et al., 2016). As it is known, landfilling, especially of composite materials, represents a high loss of high-value materials and energy input for their production, as well as loss of opportunities for reusing composites in other investments. There is a need for innovation regarding composite end-of-life disposal methods in order to integrate the materials into a circular economy mindset and increase value chain following organizational models.

The findings indicate that while significant progress has been made in recycling and reusing pultruded FRP materials, real-world challenges remain in scaling up these technologies. the study shows that co-processing in cement kilns and advanced mechanical recycling methods can contribute to a more circular economy. However, the adoption of these technologies requires stronger policy support, industrial investments, and significant advancements in scaling these processes. Without adequate infrastructure and government incentives, the widespread adoption of these methods may be delayed**.** The high costs associated with these processes and the need for specialized facilities further complicate their implementation on a global scale. Additionally, the research reveals that product remanufacturing and reuse strategies can significantly extend the life cycle of FRP components, reducing waste generation and lowering carbon emissions. However, a critical barrier to the successful implementation of these strategies is the lack of standardized remanufacturing processes and quality assurance mechanisms across the industry. In the hypothetical scenario (figure 12) discussed in this paragraph, which investigate the use of FRP for innovative ventilated facade system, the value chain operates in several distinct phases. Initially framing components are sold to facade contractors. After the components have been used, the FRP suppliers then

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repurchase the materials (either from other existing projects or from damaged work). Mostly re-manufacturer acquires old products from contractors. The next phase involves the transportation of these materials to a designated plant for remanufacturing. (physical decomposition). This involves sorting, cleaning, and grinding (mechanical recycling). During this phase, the quality of the secondary raw material (resource) is verified by a third-party lab (any contamination). Once processed, the materials are available for new reprocessing, such as re-manufacturing FRP cladding panels.

Once the remanufactured materials are ready, FRP suppliers retrieve them and stock them according to the established technical requirements for future use. These materials are not necessarily downcycled but are kept in reserve for re-manufacturing when demand arises. This system could face significant challenges related to logistical costs and inventory management, especially if remanufactured materials do not always align with market demand. Following the next step, the concept of ownership could change from the first original loop (virgin).

Finally, the remanufactured products, like FRP cladding panels, are sold to third parties or directly back to facade suppliers. This gives the FRP suppliers two valuable options: they can provide both the main framing for the ventilated facade system and the remanufactured cladding panels made from the same base material. By extending the useful life of these materials, the system helps to prevent waste generation. Products are sold through traditional channels, often at a reduced price, due to the value derived from the remanufactured materials. The specific path and options in steps four and five can vary depending on the type of product being remanufactured, such as shifting from facade framing to indoor or outdoor furniture, as an example. Despite these opportunities, market acceptance of remanufactured FRP products may be limited by consumer perceptions and regulatory barriers. FRP waste comes from production, usage, and end-of-life deconstruction. To minimize production waste, it's essential to evaluate the manufacturing process and pinpoint the most efficient methods.

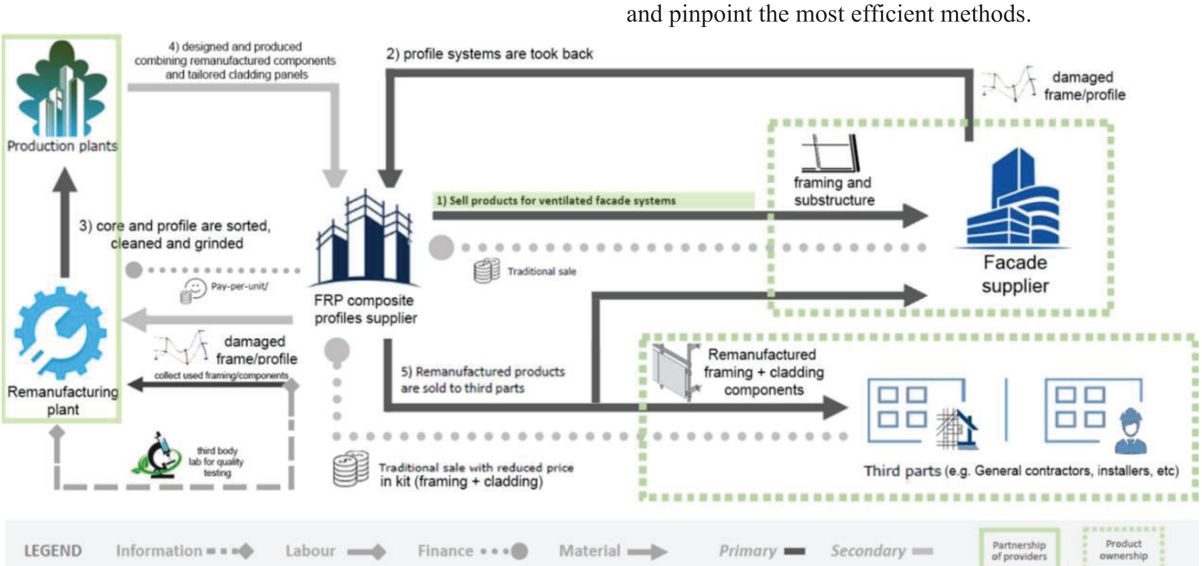

Figure 12: Exploring potential circular practices in FRP profiles industry: models and system map

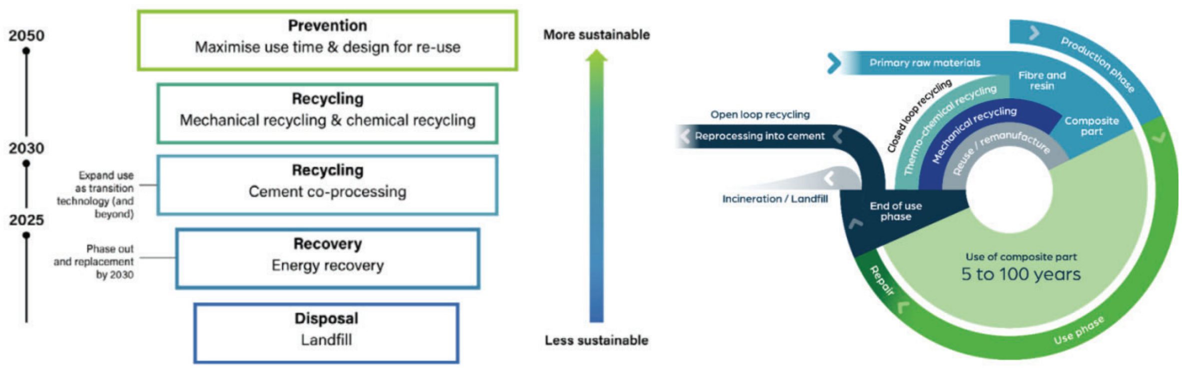

Figure 13: Proposed recycling pathway until 2030 and 2050 and composites circularity model – source adapted by the author from [UCIMU Association]

The European Commission (2018), in the document entitled *European Strategy for Plastics in a Circular Economy*, emphasizes that the low reuse and recycling rates of plastics at the end of their life cycle is a key challenge that must be addressed (Chatziparaskeva et al., 2022). Another black spot to recycling FRPs is the lack of effective separation techniques for composites during demolition**,** which could complicates their reuse. Deconstruction and reuse must be kept in mind when designing, constructing, and using FRP components for intended future reuse. Generally, automatic processes result in less waste than manual methods, but the initial cost and technological complexity of automated systems remain another black point to investigate. The use of different pre-impregnated recycled materials, different in their viscosity and stream characterized by mechanical testing and microscopy analysis - represent another possible option to transform a waste into a product with high added value, reducing the carbon footprint (Asensio et al., 2020). The aim for recycling/up cycling should be the conversion into new materials and products used in the manufacture of new composite products, enabling a circular approach within the composite sector. However, achieving this level of circularity requires overcoming challenges related to the integration of recycling systems and product design that anticipates end-of-life considerations**.** Assessing the carbon footprint of materials involves considering the emissions associated with their entire life cycle, including raw material extraction, manufacturing, transportation, installation, use, and end-of-life management.

It is important to note that specific values may vary based on factors such as production methods, energy sources, and transportation distances that must be weighted on the base of a detailed holistic evaluation. The approach for new recycling solutions has to be technology-open to identify the most suitable approach for all composite use industries. Generally speaking the recycling/disposal options about FRP products can be classified into five types: incineration, landfilling, thermal recycling, mechanical recycling, microwave and chemical recycling (figure 13). Incineration causes air pollution, CO_2 emission, and acidification of the disposal of composite products waste. Although landfills tend to have low air pollution, they can cause soil and groundwater pollution. Each of these methods comes with its own environmental and economic implications, and a careful, case-by-case evaluation is needed to determine the most sustainable approach for different types of FRP waste (also according to the waste material origin and possible contamination). Noted that a significant proportion of FRP products are thermally recycled or used as fillers in the cement industry. Microwave-assisted pyrolysis emerges as a technology with high potential to deal with the problem of recycling composite materials, since it solves traditional limitations of the pyrolysis process. The solvolysis process, or thermo-chemical recycling process, consists of the decomposition of the polymer matrix by a solution of acids, bases and/or solvent. Finally the mechanical recycling involves collection/segregation, cleaning and drying, chipping/sizing, colouring/agglomeration, palletisation/extrusion, and manufacturing the end product (Julian et al., 2022). During this process, the final new mix is composed of the same particles but in a different mixed recipe and a varying percentage of glass fibres. It is important to consider the potential fibre length reduction after the grinding process, which will affect the final properties of the recovered fibre. The new mix must be weighed, and recipe eventually modified with a minimum percentage of virgin raw materials and additives (e.g., glue primers). The variation in colour represent an opportunity (figure 14).

5 CONCLUSIONS AND FUTURE PROSPECTS

In general, pultrusion technology is innovating at a rapid pace and driving growth in the global market. One of the key driving factors for the global market growth for pultruded profiles is the rising demand for lightweight structural composite with high performance characteristics. The exploration of pultruded profiles revealed their unique characteristics, including high strength-to-weight ratio, corrosion resistance, and design flexibility, positioning them as a sustainable alternative to traditional facade materials.

Even if composite materials offer great engineering opportunities, their integration in the circular economy remains challenging. By systematically managing material flows in the circular economy framework, the application of pultruded profiles can contribute to resource efficiency, waste reduction, and sustainable practices in the construction industry. This approach aligns with the broader goals of promoting circularity, reducing environmental impact, and fostering a more sustainable and resilient economy.

Figure 14: Panel and furniture obtained from the recycling of fibreglass and rigid expanded thermosets – source [Gees Recycling Srl]

Exploring innovative building materials has become a priority to reduce the overall footprint of construction activities. Nowadays, the adoption of circular economy principles in the construction sector, has garnered attention from researchers, designer and practitioners worldwide.

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Regarding the composites, the development of a general circular business model is necessary, but also quality protocols concerning end-of-waste strategies of each individual mix of materials are needed. Ongoing research and development efforts aim to enhance the efficiency and precision of pultrusion, reducing energy consumption and expanding the range of design possibilities. Innovations may include new process to pursue the R-Strategy in composite materials. Furthermore, the LCA analysis is currently in progress to assess the environmental impacts of specific pultruded profiles, with additional results to be incorporated in future work. Other suggestions for future work could include research into the long-term durability and performance of pultruded profiles under diverse environmental conditions, exploration of hybrid composite systems to unlock new opportunities for optimizing performance and sustainability, and the integration of smart technologies into pultrusion processes, which could lead to improvements in efficiency, precision, and product quality. In conclusion, the transition to a circular economy for FRP materials requires overcoming significant technological and economic challenges, but there are viable strategies and growing opportunities that can help mitigate these barriers. Policymakers can play a crucial role in facilitating a supportive regulatory environment by offering incentives, subsidies, or tax breaks for projects that incorporate innovative and environmentally friendly materials like FRP profiles. As the construction industry continues to evolve, embracing innovative materials becomes imperative for achieving an harmonious balance between environmental responsibility, economic viability, and social progress.

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