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A1–A5 Embodied Carbon Assessment to Evaluate Bio-Based Components in Façade System Modules

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Abstract: As the construction industry moves toward sustainable building practices, incorporating wood-based materials into building envelope systems has become a priority. This paper investigates the environmental impact of three custom bio-composite Façade System Modules (FSMs) through an Embodied Carbon Assessment (ECA), focused on the Global Warming Potential indicator of life cycle stages from cradle to practical completion (A1–A5). The evaluated FSMs were developed within the Basajaun H2020 project (G.A. 862942), by substituting and combining conventional materials with other bio-composite products to form hybrids from bio-based polymers and wood. A benchmark ECA was conducted, simulating alternative FSMs devised with common practice solutions for the curtain wall façade to facilitate a comprehensive comparison. The life cycle inventory encompassed detailed technical information, fostering the utilization of primary data for accuracy. The study particularly highlights considerations over three technological systems of the modules that incorporate increased use of wood-based components and a novel bio-composite material: the frame profiles, the insulation equipment, and the seal system. Despite the challenges due to the Basajaun FSMs' weight, the findings reveal that replacing the currently used materials with wood-based materials and bio-composites reduced the embodied emissions, particularly substituting aluminum frame profiles. The insights presented here offer indicators toward circular, environmentally conscious, bio-composed building envelopes, emphasizing the need for continued analysis and refinements as a consequence of increasing the accuracy of the available primary data from the supply chain and concerning end-of-life scenarios.

Keywords: bio-based building products; bio-based materials in construction; pultruded bio-composite profiles; green buildings; embodied carbon assessment; carbon footprint; modular façade systems; sustainable construction; building envelopes; innovative design

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1. Introduction

With the escalating concerns over resource consumption and the environmental impacts of the construction sector, the shift toward sustainable practices has become imperative [1,2]. The introduction in the construction industry of bio-based materials and wood products is one of the key topics to introduce and implement more sustainable practices in the whole value chain and during the building's life [3–6]. Moreover, the bio-economy and circular economy concepts exhibit synergies, particularly in the construction sector [7], and the adoption of circular and bio-based construction practices can also yield positive outcomes for the workforce and the surrounding community [8]. However, an indispensable concern for bio-based materials' competitiveness is the provision of dependable components that exhibit controlled durability with minimal maintenance requirements [9].

However, it may not always be feasible to produce completely bio-sourced materials that possess the required attributes to fulfill construction needs. Instead, bio-composite materials have the potential to offer exceptional construction characteristics and deliver superior performance and value [10]. They can also be realized through the pultrusion process, which is a well-established practice even in civil engineering [11,12]. A bio-composite material is a type of composite material comprised of a diverse array of organic as well as inorganic components, such as bio-based and synthetic polymers. Through the combination of these materials, a novel material is produced with the potential for improved performance over the individual constituent materials [13,14]. A comprehensive review of the sustainable construction applications of natural fiber bio-composites from Ahmad et al. states that they can be renewable, cost-effective, and potential substitutes for conventional materials. These bio-composites, primarily comprised of plant-based fibers and bio-resins, have applications ranging from reinforcement in concrete to non-load-bearing members like insulation and sound absorbers, showing promising results in terms of strength, ductility, and energy absorption [15]. However, more research is needed on their life cycle assessment, cost, and long-term durability to fully understand their potential and limitations [16].

Another relevant direction in contrasting the issues of the construction sector's environmental impact is the improvements in the lean prefabrication of façade modules, thanks to their advantages in circular and low-carbon development [17–19]. A large amount of eco-conscious façade systems are available to enable high-performance building design. For designers, a challenge lies in identifying novel technologies and sustainable systems that can ensure the building's structural integrity, acoustic and thermal requirements, and aesthetic appeal [20], in addition to adequate performances, minimized carbon footprint, and other environmental impacts, as well as disassembly for reuse or recycle potential [21]. In this scenario, the introduction of bio-composite materials and systems can represent a further boost for the building envelope construction market. Indeed, the building envelope is a complex system responsible for separating the outdoor and the indoor environments, which needs to satisfy different requirements from thermal–acoustic–mechanical performances, people's safety, and various technologies' integrability. The introduction of bio-composites must comply with all these requirements. On the other hand, prefabricated façade modules can also contribute to a more circular economy. They have advantages such as reducing CO_2 emissions, assembly time, and production waste, and facilitate disassembly, maintenance, and product durability [18,22]. In the realm of bio-composite façade module systems, it can be stated, based on the current understanding and evaluation of the authors, that the most notable accomplishments in Europe have been documented in the context of the two FP7 European projects—BioBuild [23] and OSIRYS [24]. At BioBuild, the commitment has been to meet the demand for reduced embodied energy compared to conventional methods. The innovative solution involved a panel crafted from a combination of natural fibers and natural resins [25–27]. On the other hand, the OSIRYS project has yielded a diverse array of solutions for external façades in the form of building envelope products that incorporate innovative bio-composite materials [28,29].

The focus of this article is the assessment of the environmental impacts of prototypes of Façade System Modules (FSMs) that have been developed as part of the Basajaun H2020 project (2019–2024; G.A. 862942) [30]. The primary aim of this project is to optimize the utilization of wood forest resources for the purpose of constructing a medium-sized wood-based building. The optimization process involves minimizing the consumption of harvested wood from the forest by leveraging innovative wood-based construction materials (such as bio-composites) and systems (such as custom façade systems). As part of this endeavor, these materials and systems have been upscaled, and a full-scale demo building has been constructed in the village of Le Pian-Médoc (Nouvelle-Aquitaine, France) for the purpose of validation. The design of the façade system has been built partially upon the expertise and achievements of the OSIRYS project (2013–2017). With respect to the experience of it, the Basajaun FSMs have been upgraded by using the same bio-composite profiles for both opaque and vision parts. This optimizes manufacturing during off-site façade assembly. In addition, a new bio-composite profile has been realized, enabling the design of a new profile shape for the façade system. The male/female transom upgrade has been devised to enhance prefabrication and enable easier on-site installation with higher performance achievement for air and water tightness. The mechanical characteristics of the bio-composite profile have also been improved. Furthermore, the removable external cladding upgrade for the opaque façade system will allow the off-site installation of the external cladding while still providing the opportunity for its removal on-site for maintenance.

Despite its limitations, quantifying the potential contribution of emitted greenhouse gases to global warming is the most commonly used indicator for analyzing façade systems' environmental impacts [20,31]. In addition, the proposed amendment from the European Commission to the "Directive of the European Parliament and of the Council on the energy performance of buildings" can make the calculation of Global Warming Potential (GWP) even more meaningful. As it stands at the time of writing this article, if the amendment will complete the approval process, by 2027, "zero-emissions building" will replace the definition of "zero energy building" as the standard for all new buildings, and for all buildings undergoing transformative renovation from 2030 [32]. For this reason, the quantification of GWP is considered an inescapable duty. Moreover, regarding specifically the façade systems, the Centre for Window and Cladding Technology (CWCT) has emphasized the increasing significance of embodied carbon in façade assessment [33]. Considering these aspects, this article presents the results of an Embodied Carbon Assessment (ECA) conducted to estimate the greenhouse gas emissions from cradle to practical completion (A1–A5) and considerations regarding the circularity of the three experimental bio-composed Façade System Modules (FSMs) developed within the Basajaun H2020 project, emphasizing the significance of innovation and environmental accountability. All the construction requirements for these elements (i.e., acoustic, thermal, mechanical, resistance to weather elements, fire behavior) have been analyzed, simulated, and tested to comply with them. The Basajaun solutions have been developed with the target of design, and the solutions have been validated with a wide utilization and optimization of wood-based materials and bio-based polymers. However, behind the general purpose of the project, more façade-oriented objectives have been investigated, like the implementation of different types of façade systems and industrializing their prefabrication process in factories to make replication and installation easier and safer.

Particularly, the façade-oriented objective discussed in this article is the substitution of critical materials with other bio-composite products that combine bio-based polymers and wood in order to increase wood use and wood-based products in the façade system, reducing the carbon footprint and improving circularity.

2. Materials and Methods

2.1. Façade System Modules and Their Technological Systems

During the Basajaun project, three tailored Façade System Modules (FSMs) were developed. This article focuses on these modules of varying types and functions, along with their respective components, which serve as research materials for the environmental assessment presented in the article. Figure 1 shows a picture of these FSMs during the testing phase. The modules, which are 4.0 m tall and 1.2 m wide, have been defined as:

- Basajaun Glazed Vision FSM: This is a curtain wall module that is primarily composed of glass (about 500 kg in weight);
- Basajaun Opaque FSM: This is an opaque curtain wall module that does not contain any glass. It is typically used for areas of the building envelope that require more insulation or where transparency is not desired (255 kg in weight);
- Basajaun Window FSM: This is a curtain wall module that includes both glazed and opaque elements. The glazed portion allows for natural light, ventilation, and visibility, while the opaque portion, referred to as a spandrel portion, can hide building components or provide additional insulation (385 kg in weight).

(a) (b)

Figure 1. (**a**) Picture of the Basajaun Façade System Modules performance mock-up; (**b**) Detail picture of the Opaque and Window modules facing. Frame profiles in bio-composite.

Each module was meticulously crafted with an emphasis on wood-based materials, advanced technologies, and adherence to stringent performance standards. The overarching goal was to create an innovative and environmentally conscious building envelope that aligns with market requirements.

Starting with the Glazed Vision Module, it represents a fusion of aesthetic appeal and functionality. Structurally sealed glass is seamlessly integrated into bio-composite frame profiles. The bio-composite material is a key innovation, featuring a balance of bio-based resin, basalt fibers, and wooden particles. The module undergoes comprehensive mechanical, thermal, and acoustic simulations, affirming its resilience and thermal efficiency. The commitment to energy efficiency is further underscored by a detailed thermal analysis, meeting or exceeding the defined standards.

Moving on to the Opaque Module, the architectural element is marked by an integration of diverse materials and technologies. The internal layer consists of a plywood plate, providing structural integrity combined with the frame of bio-composite profiles (same as in the other FSMs), providing structural integrity as the foundation for subsequent components. Wood fiber insulation panels, with a minimum of 80% wood content, contribute to thermal efficiency. Membrane and sheathing systems, such as the plywood panels, eschew traditional aluminum cladding. The module undergoes thorough mechanical and thermal simulations, ensuring optimal performance under varying conditions. The incorporation of steel plates for connections is necessary to enhance stability and facilitates maintenance and disassembly.

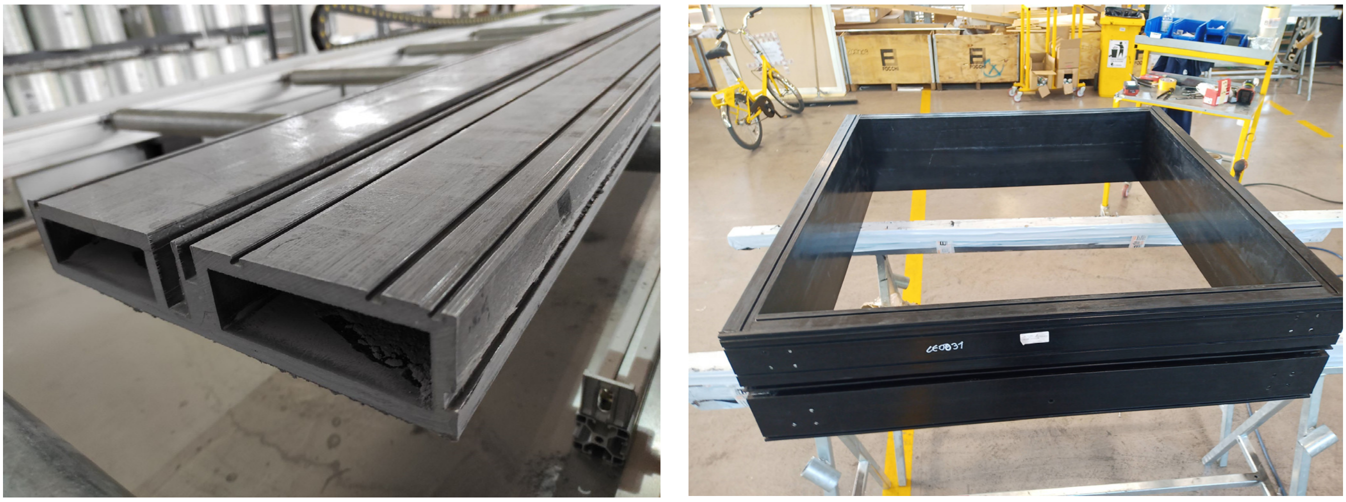
The Window Module integrates a window block with a shading system through an external roller shutter. The façade frame introduces the new bio-composite profile, aligning with the commitment to sustainable materials. The utilization of wood-based insulation and membranes in sealing systems enhances the thermal efficiency while reducing the environmental impact.

The three FSMs incorporate the increased use of wood-based components and a novel bio-composite material in three key technological systems: the frame profiles, the insulation equipment, and the seal system. The subsequent sub-sections unveil the alternative solutions that have been devised for each system.

2.1.1. Bio-Composed Frame Profiles

The façade module's frame profiles are carefully crafted to complement the architectural design. The vertical mullions and horizontal transoms are strategically composed to withstand mechanical stresses, adhere to module dimensions, and uphold the moment of inertia [34]. The Basajaun project entails the meticulous crafting of pultruded custom bio-composite profiles. Pultrusion technology is a continuous process where reinforcing fibers, such as fiberglass, are impregnated with resin and then pulled through a series of dies and cured to form a continuous profile. It is employed for manufacturing, ensuring a constant section composite with high mechanical strength [35]. On the other hand, extrusion, which is used for the crafting of an aluminum profile (most commonly used for FSMs), involves forcing a material through a die to form a profile with a constant cross-sectional shape.

The Basajaun bio-composite profiles feature a blend of components, primarily composed of a bio-based resin system and basalt fiber reinforcement. With a meticulous material ratio, the reinforcement accounts for 55%, comprising endless roving fibers and various types of woven roving. The resin system, constituting 45% of the composite, is a complex amalgamation of elements. Notably, 30% of the base resin is bio-based, incorporating succinic acid instead of conventional orthophthalic or isophthalic acid and recycled components. The bio-based resin system is enriched with a range of additives, including a shrinkage reducer, internal mold release agent, accelerator, catalyst, color paste, and air bubble remover additive. Additionally, 3% of the resin system is comprised of wooden particles, all of which are bio-based. The bio-based content is calculated by taking into consideration the proportion of the bio-based resin and the wooden particles. The resulting bio-based quantity stands at approximately 11.5% of the total mass. Numerous tests were conducted to ensure that the bio-composite profile meets the necessary requirements as a façade profile. This article will not delve into the specific characteristics of the material, but some test results will be provided to facilitate a better understanding of it. According to UNE EN ISO 527-4:1997 [36], the axial tensile strength of the profile is 409 MPa, and the axial modulus of elasticity (Ef) is 24,900 MPa. Additionally, results from axial compression strength tests according to UNE-EN ISO 14126:2001+AC:2002 [37] show a modulus of elasticity of 34,600 MPa, a compressive strength of 443 MPa, and a deformation in compressive strength of 1.8%. The thermal conductivity is 0.58 W/mK, assessed by the manufacturer within the project development. It is worth noting that even if durability analyses of the material were not conducted during the project, aging tests were conducted to evaluate the tightness of tapes and sheets. The Basajaun bio-composite profiles are depicted in Figure 2.



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

Figure 2. (**a**) Picture of the Basajaun bio-composite pultruded mullion profile; (**b**) Picture of the bio-composite frame of a Basajaun mock-up module.

2.1.2. Wood-Based Insulation Equipment

Insulation plays a pivotal role in enhancing the performance of the entire façade system [17]. Its primary function is to maintain the indoor temperature, and it also significantly contributes to the energy efficiency of the building [38]. In the Basajaun Façade System, the insulation is entirely wood-based. The wood fiber insulation panels used are crafted from a combination of base and ancillary materials, ensuring a high-performance solution. The primary constituent is wood, with a minimum content of 80%, predominantly sourced from pine and supplemented by some hardwood. Notably, a minimum of 70% of the wood used is certified by the Program for the Endorsement of Forest Certification (PEFC) attesting to sustainable forestry practices [39]. Binding fibers contribute to the structural integrity of the panel, comprising 3–8% of the composition. The incorporation of these fibers enhances the material's overall strength and durability. Additionally, the panel contains water in the form of wood moisture, ranging from 4–8%, and ammonia phosphate, constituting 6–8% of the material. The material possesses specific characteristics as per the established required standards. The noteworthy characteristics are the gross density (as per EN 1602 [40]), which is 55 kg/m^3, the thermal conductivity (as per EN 13171 [41]) of 0.038 W/(mK), and the water vapor diffusion resistance factor (as per EN 12667 [42]), which is 5. The wood fiber insulation placed in a mock-up module is depicted in Figure 3.

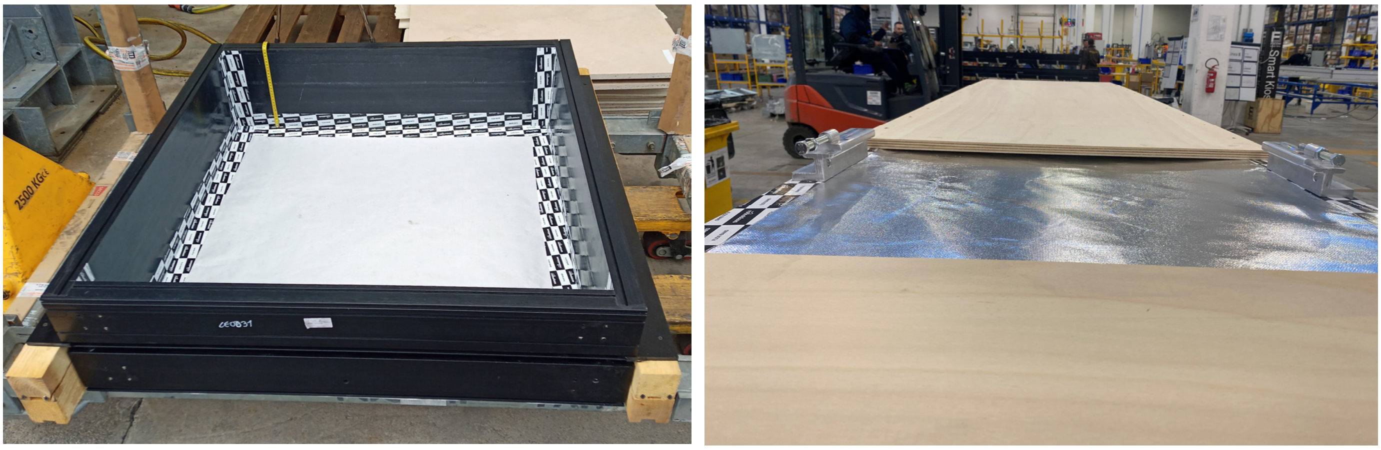
Figure 3. Picture of the wood fiber insulation panel placed in a Basajaun mock-up module.

2.1.3. Seals and Gaskets

Ensuring the building's envelope is protected from moisture and weather damage is a complex process that depends on various factors [43]. Thus, properly sealing a building's façade with non-combustible materials is critical for fire safety. Therefore, sealing the interfaces of the FSMs helps prevent the spread of fire by restricting airflow and flames. The Basajaun Façade System limits the use of aluminum sheets and silicon in façade modules.

The Basajaun FSMs incorporate three distinct sealing products used to enhance their functionality and performance. The first sheet features a reflective fire reaction vapor barrier screen, comprising an upper layer of aluminum film and a lower layer of fiberglass fabric. The second sheet is a highly breathable reflective membrane; its composition includes a protective layer of perforated aluminum film, an intermediate layer of functional PE film, and a bottom layer of fiberglass fabric. The third element, a double band, consists of layers that contribute to robust adhesion and reinforcement. It involves a separating layer of silicone-coated paper, solvent-free acrylic dispersion adhesive, a reinforcement grid made of polyester, and another layer of solvent-free acrylic dispersion adhesive. These diverse sealing products collectively contribute to the product's versatility, combining reflective properties, breathability, fire resistance, and robust adhesion for a comprehensive and effective solution.

On the other hand, the plywood panels' primary component is wood, constituting about 84%. This wood content encompasses a balanced selection of quality wood materials, contributing to the panel's overall strength and stability. To enhance the structural cohesion of the panel, 11% of the composition is resin, 0.16% is mastic, and 0.16% is additives. For additional reinforcement, the panel features hardener and water, accounting for 5%, and glued tapes and composing glue, comprising 0.04% of the composition. Tapes, membranes, and plywood placed in a mock-up module are depicted in Figure 4.



(a) (b)

Figure 4. Picture of tapes, membranes (**a**), and plywood manels (**b**) placed in a Basajaun mock-up module.

These technological systems work together to ensure the FSMs are safe, functional, and efficient, contributing to the overall performance of the building.

2.2. Environmental Assessment Methodology

In order to be able to make more precise assessments regarding the environmental impact of these façade systems, the Global Warming Potential (GWP) of the modules was quantified. This was achieved by performing an Embodied Carbon Assessment (ECA) of all three FSMs considering a boundary from cradle to practical completion. During the calculation of the embodied carbon, the Centre of Window and Cladding Technology's method indications were considered [44]. With reference to the life cycle assessment (LCA) method defined by ISO EN 14044 [45,46]. After the goal and scope definition phase, defining the reasons for applying this methodology to the project, the other two phases of the ECA as defined by the norm were applied.

2.2.1. Life Cycle Inventory (LCI)

This phase involves calculating the input and output flows throughout the entire supply chain, based on the LCA methodology. This includes measuring quantities of components and materials, assuming their waste generation, and their consequential greenhouse gas emissions. Once the reference system flows are defined, the impacts are calculated using various stages defined by the standard. The presented study stages from cradle to practical completion have been considered (A1–A5). These stages include collecting quantitative project data on materials and components, as well as environmental data from primary (foreground) and secondary (background) sources.

2.2.2. Embodied Carbon Assessment Results

This last phase involves the final assessment by associating the LCI results with the environmental factors. The results presented are focused on GWP, the best known and most requested impact assessment category. Considering the limitations of this methodology when applied to bio-based materials [47] and that GWP is one of several categories of environmental impact, the results were analyzed considering biogenic carbon sequestration as emitted carbon dioxide during raw material supply.

3. Results

To better understand the environmental impact of the Basajaun Façade System Modules (FSMs), their Global Warming Potential (GWP) was quantified through an Embodied Carbon Assessment (ECA). Given the Basajaun H2020 project context, one of the goals is to assess the environmental performance of the façade modules from their raw material extraction to installation on the construction site. To that aim, the Embodied Carbon Committee of the Centre for Window and Cladding Technology (CWCT) published a report in 2022 that presents a peer-reviewed methodology for assessing the embodied carbon of façades [44]. This procedure focuses on the GWP environmental impact indicator and aligns it with whole-life carbon assessment documents from other construction industry bodies. The methodology is also aligned with the life cycle assessment (LCA) method, as defined by ISO EN 14044 [45,46], and considers the life cycle boundary as defined by EN 15804 and EN 15978 [48,49]. However, while designers and assessors should ideally consider as many life cycle modules as possible, CWCT has identified the minimum life cycle stages that should be included in a façade assessment. These stages include the product stage (A1–A3), construction process stage (A4–A5), replacement stage (B4), and end-of-life stage (C1–C4). The study presented herein has placed a particular emphasis on the A1–A5 stages due to a dearth of foreground data pertaining to the stages subsequent to practical compliance.

This methodology was applied to the three FSMs developed within the Basajaun project. Then, in order to establish a benchmark reference for the analysis and interpretation of the results, an ECA A1–A5 of parallel FSMs conceived as conventional was conducted, assuming the use of conventional materials and common practice solutions for the curtain wall façade for the different technological systems that met the same design requirements. Each technological system was then examined to identify alternatives that provided the same mechanical, thermal, and sealing performance as the Basajaun system. This led to the consideration of aluminum frame profiles in comparison with bio-composite profiles according to their mechanical characteristics and thermal resistance, mineral wool insulation in comparison with wood fiber according to their conductivity and density, and traditional sealing systems with gaskets and silicones in comparison with tapes and sealants according to their water and air tightness, as well as the use of aluminum sheets instead of plywood panels. No alternative glazing was considered due to its unique functionality. Other components, such as screws, nuts, and surface treatments, were assumed to be identical in both Basajaun and benchmarking versions, as their negligible mass and negligible CO_2 emissions made them inconsequential to the overall GWP comparison. Additionally, based on BS EN 15978 Section 9.4.3 and BS EN 15804 Section 6.3.6, components that do not exceed 1% of the façade system mass could have been excluded from the GWP calculation [48,49].

By emulating the process in a conventional manner, the aim was to assess the GWP consumption patterns of Basajaun FSMs against an abstraction of how they would have been as conventional. This approach not only provides a more comprehensive understanding of the unique characteristics of the custom design but also facilitates comparison by highlighting deviations from traditional practices.

3.1. Life Cycle Inventory

The technical information related to the manufacturing of the FSMs has been produced after completing the design stage. A comprehensive bill of supplies detailing all the necessary materials and components, along with technical drawings outlining the assembly steps and machining procedures, has been drafted for each module. Considering them, once the reference system flows have been defined as related to energy consumption, consumption of raw materials or waste, or greenhouse gas emissions, their GWP was calculated through the A1–A5 life cycle stages defined by the standard EN 15978 [49]. This inventory step requires: (1) the collection of quantitative project data on materials and components used and (2) the collection of environmental data (i.e., carbon factors) from primary (foreground) and secondary (background) sources to evaluate the impact of the project. To ensure accuracy and reliability in analyzing the as-conventional module quantitative project data related to material composition and consumption, they were adjusted using conversion factors selected based on manufacturer information and research. This approach ensured that the virtual representation of the as-conventional modules reflected the anticipated material quantities that would be utilized in a common construction scenario. The sources of the data used in the ECA are indicated in Table 1, about the project data, and in Table 2 about the environmental data.

Table 1. Summary of the project data sources.

A1	
Modules' materials and components	Bill of components, products' datasheet, company's PLM and ERP, technical drawings, BIM model.
A2	
Materials and components' shipping information	Geographical position of the suppliers, company's PLM, ERP, and departments' worksheets, DDT.
A3	
Module manufacturing	Production plans.
A4	
Transport to the construction site	Geographical position of the construction site, shipping plans, company's PLM, ERP, and departments' worksheets, DDT.
A5	
Machine or plant usage on site due to modules' installation	Production and construction company.

Table 2. Summary of the environmental data sources (i.e., carbon factor sources).

A1		**FU**
Frame profiles		
Aluminum profiles	European Aluminum. Environmental Profile Report [50].	kg
Bio-composite profiles	Eco Impact Calculator for composites v.1.1.1 [51], primary data from the manufacturing company, and Azrague et al. [52].	kg
Insulation equipment		
Rock wool	Average from EPDs of panels with similar density and thermal conductivity.	m^3
Wood fiber	Used product EPD.	m^3
Seals and Gaskets		
Aluminum sheet	Aluminum Sheet European avg. Environmental Profile Report [50].	kg
Plywood	Used product EPD.	m^3
Tapes and sealants	Average from EPDs of products with similar characteristics.	m^2
EP and vulcanized seal	Ecoinvent v.3.7.1: Synthetic rubber [53].	kg
Other components		
IGU	Generic values CWCT [33].	m^2
Roller shutter	Average from EPDs of products with similar characteristics.	m^2
Finishing	Ecoinvent v.3.7.1: Powder coat, steel [54].	m^2
A2–A4		
Transport	Ecoinvent v.3.7.1: Transport, freight, lorry EURO5 {RER} ∣ avg 3 to >32 metric tons [55].	$kg_{tran.ted} \cdot km$

Table 2. *Cont.*

A1		**FU**
A3		
Assembly off-site	Primary data from the manufacturing company.	
A3 waste rate	How to calculate the embodied carbon of façades: a methodology; CWCT [44].	WRi = 3%
A5		
Energy consumption	Report of emissions per kWh of the regions of the construction sites.	
A5 waste rate	How to calculate the embodied carbon of façades: a methodology; CWCT [44].	WRi = 3%

Given the significance of the implementation of bio-composite profiles in this study and the noteworthy interest surrounding them, it is deemed pertinent at this point to expound on the outcomes derived from the compilation of data pertaining to these innovative profiles.

Based on the composition outlined in Section 2.1.1, percentages were assigned to the mass unit relative to its contents, with 55% of the composite of reinforcement and 45% of the resin system. Every effort was made to attribute a carbon factor to each content, with a focus on foreground factors. However, the suppliers of the FSM components could not provide primary data about their impact; as a consequence, secondary data was utilized. To estimate their carbon factor, the Eco Impact Calculator for composites 1.1.1 was utilized. This digital tool enables the calculation of the environmental impact of composite products, from cradle to gate, as provided by the European Composites Industry Association (EuCIA). The background datasets for this tool are sourced from the SimaPro 9.3.0.3 software, and it is supplemented by industry data obtained through completed questionnaires [51]. However, it appears that there is still a lack of specific data regarding the content of the bio-resin system in the given quantities, as well as the reinforcement basalt fibers. As a result, it has been necessary to make assumptions about their carbon factors assuming one related to polyester resin and glass fibers, respectively. As a result, the carbon footprint calculated by the software of 1 kg of Basajaun profile is equal to 2.98 kgCO_2eq/kg. However, based on a thorough review of the relevant scientific literature to identify more specific carbon factors, revised calculations were carried out. In light of the carbon factor reported by Azrague et al. for a comparable basalt fiber reinforcement content [52] and more precise calculations regarding the consumption of the pultrusion process, the new calculations were conducted. Upon careful consideration, it has been determined that the carbon dioxide equivalent emissions associated with the retrieval of raw materials for one kilogram of the bio-composite developed in the Basajaun project amount to 1.67 kgCO_2eq/kg. Afterwards, when it comes to estimate pultrusion-related emissions, which is claimed to be one of the most cost-effective and competitive approaches to obtaining constant section composites [56,57], the operational parameters are critical in determining energy consumption. The pulling equipment used, according to the machine technical datasheet, requires 13 kW of unit power, while about 6 kW is allocated for heating the production dies. This is assuming 2/3 of the maximum heating power of 9 kW as, in the context of series production, maintaining a consistent level which is imperative and the exothermic heat generated during the process aids in heating up the die. Therefore, when calculating the energy used in one hour of the pultrusion process, the total reaches 19 kWh. The average pulling speed ranges from 0.25 to 0.30 m/min, which translates to 15 to 18 m/hour, and 180 to 216 kg of profiles. Consequently, the energy consumption per kilogram of the pultruded main profile is estimated to be between 88 and 105 Wh/kg. Considering the greed carbon factor of the pultrusion plant region, of 215 gCO_2eq/kWh, it has been assumed a carbon factor for the pultrusion process of the Basajaun bio-composite profile of about 0.021 kgCO_2eq/kg. On the other hand, in the extrusion realm, average pulling speeds range from 3 to 12 m/min, requiring 45 to 90 kW of power, with an output ranging from 150 to 250 kg per hour. That means applying the same greed carbon factor as the pultrusion plant would achieve 0.072 $kgCO_2eq/kg$. Despite the bio-composite profiles, which have been specifically designed for the structural frame (as the one depicted in Figure 2), exhibiting a notable weight of 12–15 kg/m. It has been determined that a conventional extruded aluminum profile, when subjected to identical loads and tension, would weigh approximately 7 kg/m. However, it is important to note that these values are approximate, as precise measurements have not been conducted during the design and production.

The article refrains from specifying additional data assumptions for other technological systems, owing to the fact that they are composed of materials that are more prevalent and conventional in the market. As indicated in Table 2, Environmental Product Declarations (EPDs) have been made available for insulation and plywood panels.

3.2. Embodied Carbon Assessment Results

The last stage involves the final assessment by associating the collected data in the ECA results. It is important to note that the impact of phase A1 should be understood as the impact of the components of the façade module. Therefore, the A1 impact of a component belonging to an FSM does not solely refer to the extraction of its raw materials but also to their pre-processing in other plants. For example, in the study presented here, item A1 of a bio-composite profile corresponds to the extraction of its raw materials, its transportation to the plant where it was pultruded, and the impact of the pultrusion.

Furthermore, prior to presenting the results, it is crucial to highlight that the findings regarding the influence of transportation in the supply chain do not represent a typical supply chain. This is because the modules being analyzed are part of a European initiative (Basajaun project) involving industrial partners located across the continent, such as Italy, Spain, and Hungary. Consequently, the impacts related to transport (A2 and A4) are probably higher that what they would be in a typical supply chain.

In the subsequent sub-sections, the outcomes of both the Basajaun FSMs and the as-conventional FSMs have been expounded through a series of explanatory graphs. These graphs have been categorized based on the three FSMs, namely Glazed Vision FSM (Figures 5–7), Opaque FSM (Figures 8–10), and Window FSM (Figures 11–13).

3.2.1. Glazed Vision FSM

Each FSM sub-section includes a histogram that compiles the GWP results from the five stages of the module life cycle. The first column displays results from the as-conventional module (light blue), while the second column shows results from the Basajaun module (green). The values from different stages have been merged in different manners to better understand their impact on the total. The values represent the impact of the entire façade modules, which are 4.0 m tall and 1.2 m wide ($kgCO_2eq$) or they are normalized to m^2 ($kgCO_2eq/m^2$) depending on the bar description in the histogram. The mass of the modules differs depending on the FSM type; it is about 500 kg for the Glazed Vision FSM, 385 kg for the Window FSM, and 255 kg for the Opaque one.

In all three cases, the stage causing the highest emissions is A1 due to the complexity of the components of the façade modules. According to the findings, the A1 stage of the bio-composite version yields 9.64×10^2 $kgCO_2eq$ (2.01×10^2 $kgCO_2eq/m^2$), whereas the as-conventional version results in 1.15×10^3 $kgCO_2eq$ (2.39×10^2 $kgCO_2eq/m^2$). Furthermore, the factory responsible for assembling the components is powered by photovoltaic panels, and the site operations are confined to module installation and sealing operations. As a result, the environmental impact of these stages is remarkably low if compared to A1. A3 values are invariant across both versions, yielding a result of 1.14×10^1. This is attributed to the assumption of an equal assembly process for all the FSMs. A5 values differ slightly between the as-conventional and Basajaun versions. In the as-conventional version, the A5 value is 4.59×10^{-2} $kgCO_2eq$, whereas in the Basajaun version, it is 5.05×10^{-2} $kgCO_2eq$ due to the increased weight.

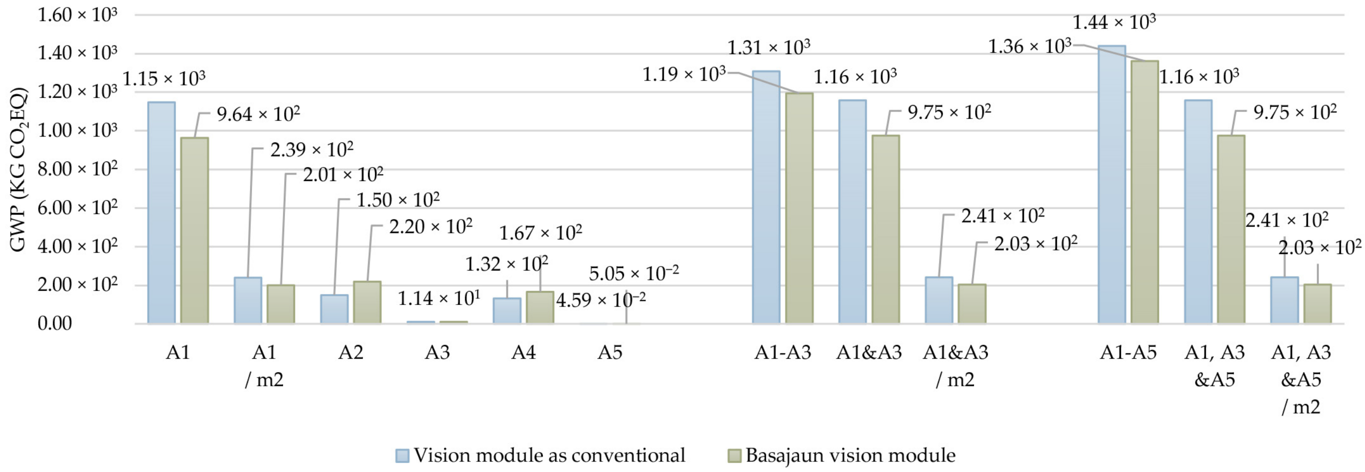


Figure 5. Comparison of the Basajaun and as-conventional Glazed Vision FSM results: A1–A5 GWP.

The second histogram displayed in each FSM section provides a more detailed analysis of the impact of individual technological systems, as previously presented in Section 2.1.1. The GWP values encompass all components of the FSM.

These are the only charts where the impact considering the carbon included in the wood-based products is presented, referred to as "Basajaun—Considering biogenic carbon stored in the materials." Biogenic carbon is derived from biological sources and is associated with the carbon stored in the biomass. When conducting an ECA or an LCA, the carbon in these products is usually considered separately from fossil carbon, which comes from non-renewable sources. Trees absorb carbon dioxide during growth and store it in their biomass. When harvested and used to make products, this stored carbon contributes to a negative value in the GWP. This carbon sequestration aspect is a key reason why wood products are considered environmentally beneficial, as they can help offset carbon emissions. Although there is no consensus on the assessment of biogenic carbon in LCA, different methodological choices and assumptions can lead to opposite conclusions [58]. For this reason, it is important to clearly state how this is considered. In the presentation of the findings, the discounting of biogenic carbon dioxide was considered valuable to ensure a more effective comparison of the proposed solutions despite the narrow boundary. In the A1 values displayed, the biogenic carbon is then considered as actual emissions. Nonetheless, given its significance, a bar has been included to reflect the results of the Basajaun module in the event that it is taken into account (Figures 6, 9 and 12).

Specifically, Figure 6 pertains to the Glazed Vision module that lacks a spandrel portion and therefore has no insulation-related impacts. Notably, the "other components" category presents high values due to the inclusion of glass, which comprises the major surface and mass of the module. Finally, since bio-composite profiles have a limited wood-based component and since there are no plywood panels, the reductions given by biogenic carbon are not significant.

In each FSM section, the final figure provides a more precise breakdown of A1's GWP, detailing each component type within the analyzed module. The left side displays graphs related to the as-conventional module, while the right side displays graphs related to the Basajaun-developed module. Components and materials assumed as unchanged between the two versions are represented in grayscale, while components belonging to different technological systems are shown in color to aid in comparison. The histograms display absolute values for the entire module, while the pie charts illustrate the components' perceptual impact on the total A1 GWP. The height of the bar and the corresponding value above it reflect the outcome derived from the primary environmental data gathered during the LCI phase. Conversely, the error bar signifies the potential variance in results that could arise from utilizing secondary data from external databases or considering alternative suppliers.

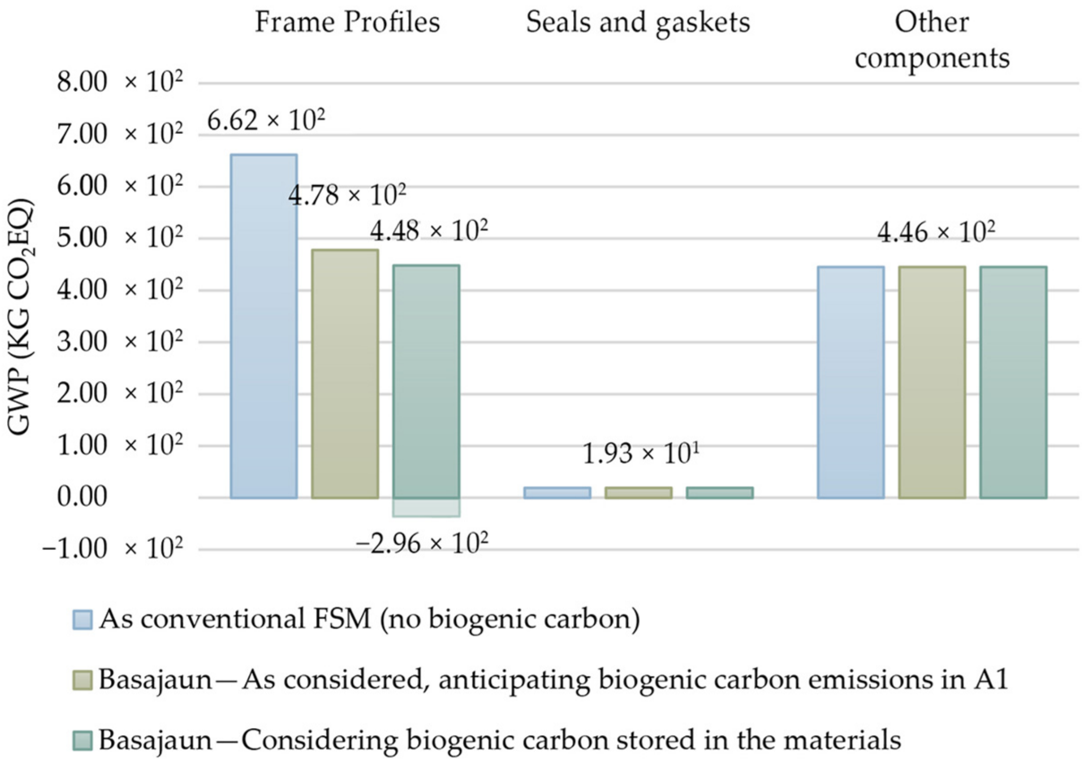


Figure 6. Glazed Vision FSM technological systems comparison of A1 GWP.

The figure related to the Glazed Vision FSM is Figure 7; it reveals that the primary contributors to emissions of this FSM are the frame profiles and glass components. It is notable that the Glazed Vision system demonstrates a reduction in the GHG emissions only regarding the structural profiles, benefiting from bio-composed materials with respect to aluminum profiles. The item labeled as 'Extruded profiles' in the two diagrams, which also appears in the following FSM sections, encompasses all the connection elements that are integrated into the module. These elements had to be made of either stainless steel or aluminum due to structural safety considerations.

The comprehensive error bar observed in the aluminum profiles—which, as pointed out, represents possible alternative outcomes by assuming different data—is due to the variability of GWP among similar aluminum-extruded products in the market. The values used for evaluating aluminum profiles in the as-conventional FSM are obtained from the Environmental Profile Report [50], whereas profiles containing 36% recycled aluminum are indicated as the European average. However, some exceptional products available in the market contain 75% recycled content and possess environmental certifications that attest to GWP per kg values that are 45% lower than the values used in this analysis [59]. Conversely, some international databases report values that are up to four times higher than the values used in this study [60]. These factors contribute to the large error bar observed in the graph for aluminum profiles. Then again, the error bar pertaining to the profiles in bio-composites is representative of the value that would have been obtained had the result been derived from the Eco Impact Calculator for composites 1.1.1 from EuCIA.

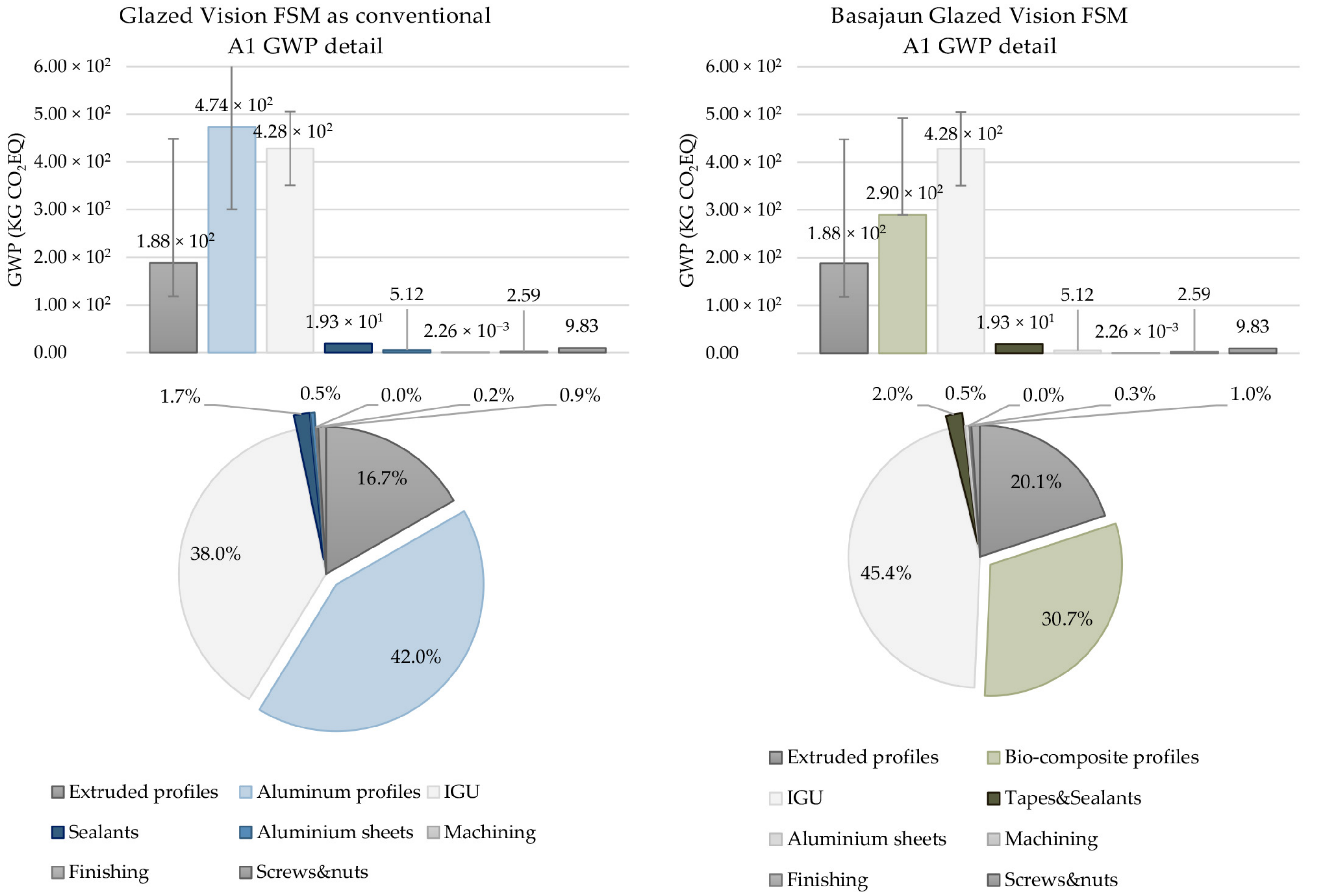


Figure 7. Comparison of the Basajaun and as-conventional Glazed Vision FSM results: A1 GWP detail.

3.2.2. Opaque FSM

As for the previous FSM section, the first figure, Figure 8, displays a comprehensive cross-section of the results obtained from the different GWPs analyzed in various stages. As for the Glazed Vision module, the impacts of A3 and A5 are relatively inconsequential compared to the other factors. The GWP of A1 for the Basajaun Opaque module is 6.38×10^2 $kgCO_2eq$ (1.33×10^2 $kgCO_2eq/m^2$), while that of the as-conventional module is 8.60×10^2 $kgCO_2eq$ (1.79×10^2 $kgCO_2eq/m^2$).

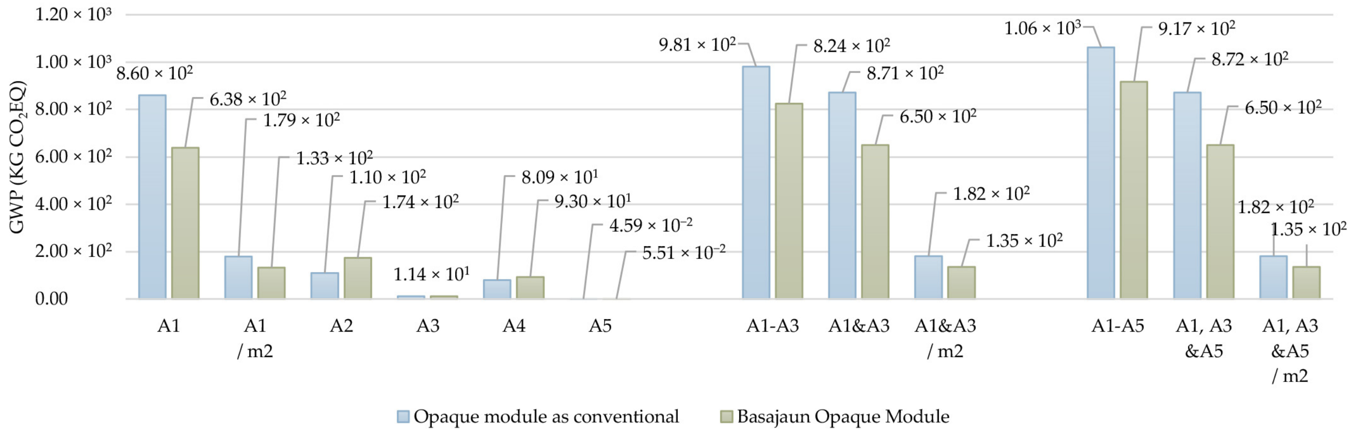


Figure 8. Comparison of the Basajaun and as-conventional Opaque FSM results: A1–A5 GWP.

In Figure 9, a closer look at A1 GWP is presented. Since it is about Opaque FSM, the impact of insulation equipment and the part about sealing and related aluminum sheets or plywood panels appear in the graph. When comparing the results of the as-conventional FSM, it becomes evident that the impact related to the aluminum-extruded profiles is higher than the impact of insulation and seals equipment. However, with the Basajaun FSM, the impact of various factors is more evenly balanced and lower overall. It is worth noting that when considering biogenic carbon in the Basajaun modules, the items related to insulation and sealing exhibit significant variation. Specifically, with wood fiber panels, the majority of GHG emissions are associated with the release of embedded carbon during end-of-life disposal.

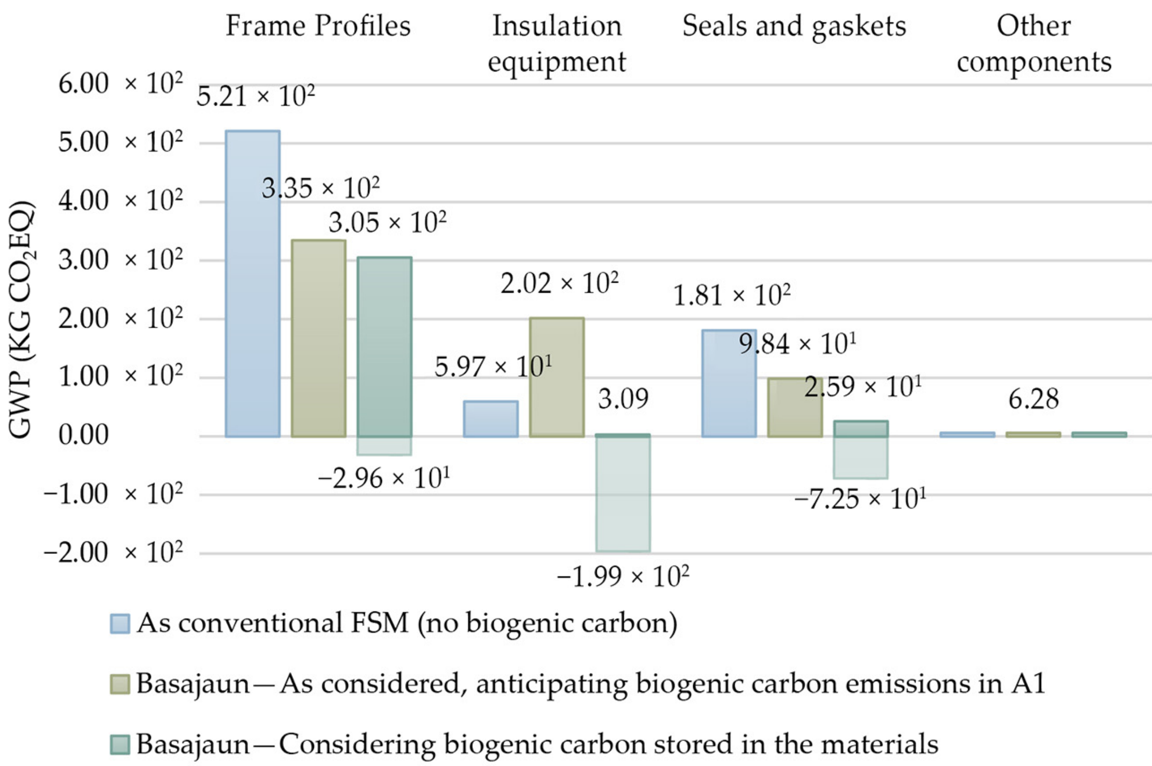


Figure 9. Opaque FSM technological systems comparison of A1 GWP.

Figure 10 presents detailed graphs of the impact of stage A1 on the Opaque modules, revealing insights. The as-conventional module shows that almost all of its impact is attributed to extruded profiles and aluminum sheets, which account for 94.9% of the total. In contrast, the Basajaun module balances this percentage with a combination of extruded and pultruded profiles (55.6%) and plywood (11.8%), due to the significant impact of wood fiber insulation (31.5%). It is important to note that biogenic carbon was considered in this graph as emitted in A1.

One can also observe the significant error bars of the insulation equipment in both versions. The EPD of the products used in making the mock-up was used for the analysis, and the histogram bar represents its value. However, the error indicates the result that could have been obtained with other similar products available on the European market whose EPD was public.

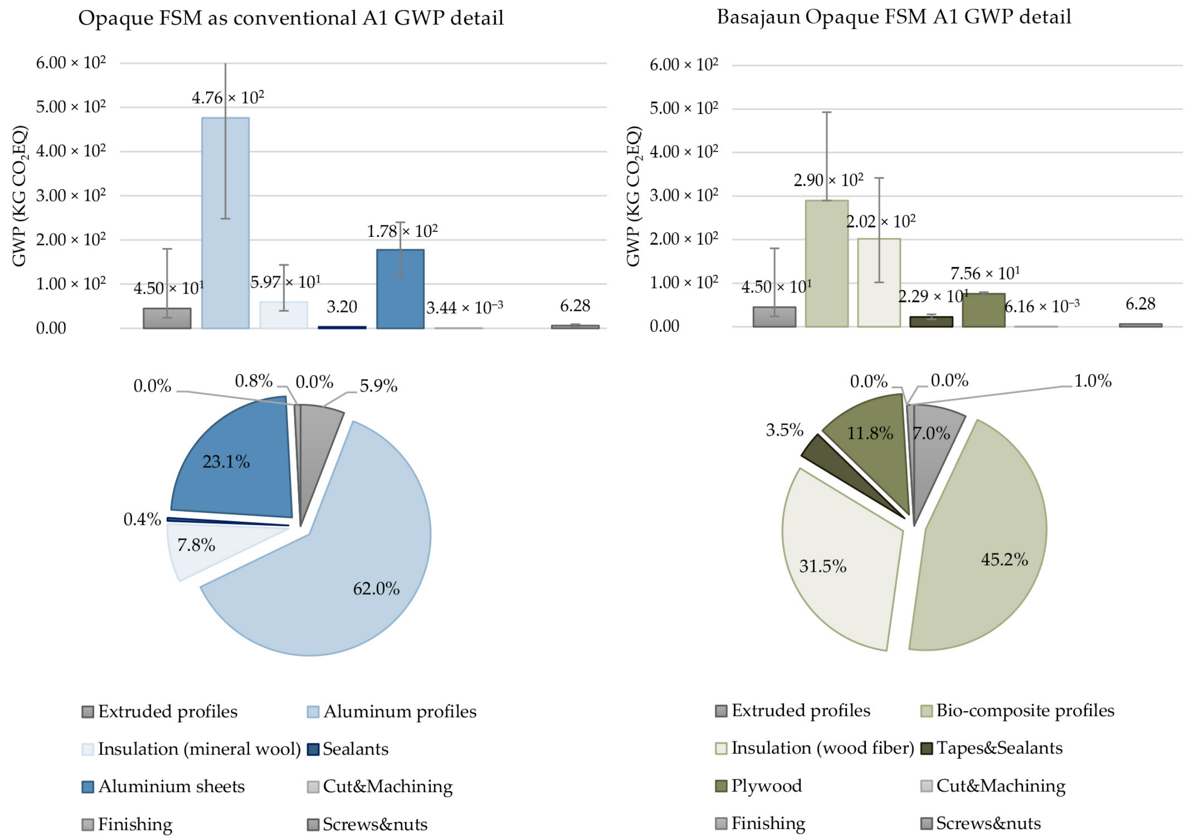


Figure 10. Comparison of the Basajaun and as-conventional Opaque FSM results: A1 GWP detail.

3.2.3. Window FSM

After analyzing the three FSMs, it was observed that the Window module had a more elevated impact compared to the other two. The data reveals an A1–A5 GWP of 1.52×10^3 kgCO_2eq (3.16×10^2 kgCO_2eq/m^2) for the Basajaun model, whereas if it had been designed as conventional, 1.71×10^3 kgCO_2eq (3.56×10^2 kgCO_2eq/m^2). The detailed results are presented in Figure 11.

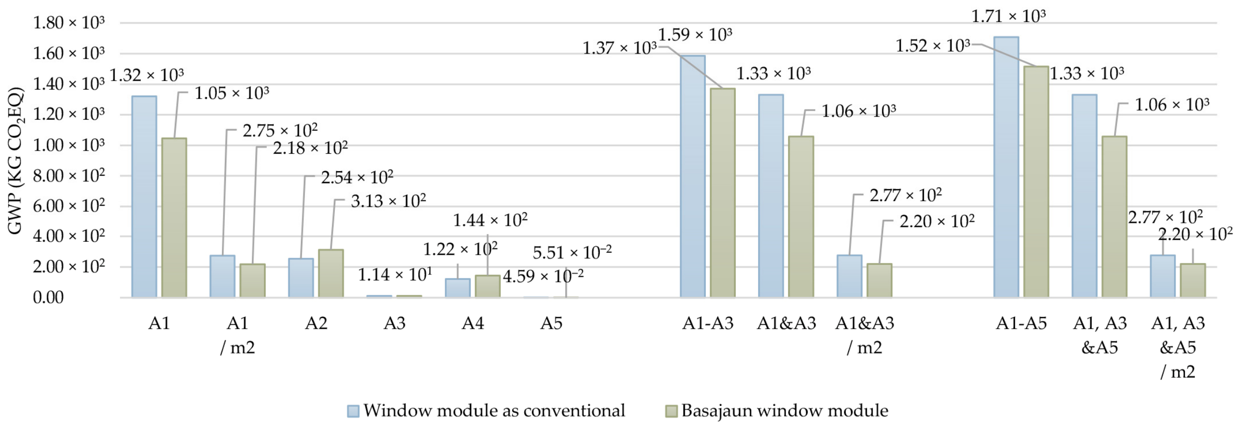


Figure 11. Comparison of the Basajaun and as-conventional Window FSM results: A1–A5 GWP.

The assessments pertaining to Figure 12 mirror those of Figure 9. Nevertheless, it is worth noting that the frame profiles exhibit a higher GWP value owing to their added responsibility of accommodating an opening window, thereby requiring more and larger sections. The "other materials" category also shows an increase due to the inclusion of the window glass.

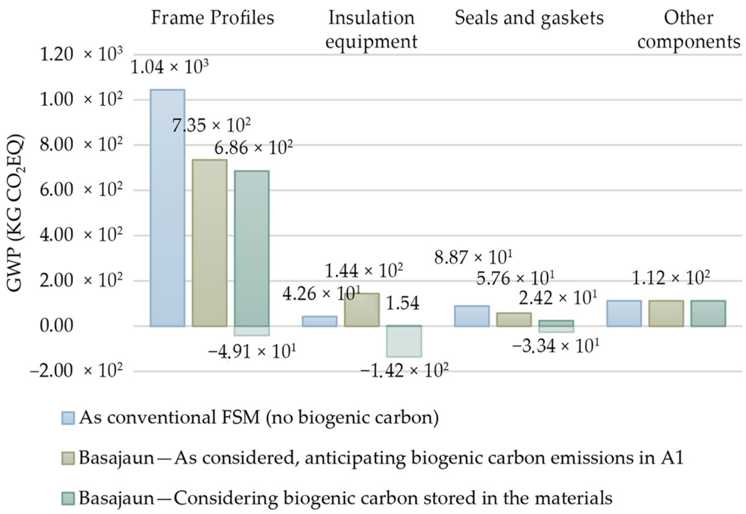


Figure 12. Window FSM technological systems comparison of A1 GWP.

Analogous to the other sections within the FSM, the final figure in this series illustrates the specifics of the results for A1 GWP, as seen in Figure 13. The profiles carry a greater weight, resulting in a more pronounced indicator for them. In contrast, the glass component holds less weight compared to the Glazed Vision FSM, since it only covers a smaller surface area of 1.1 m^2.

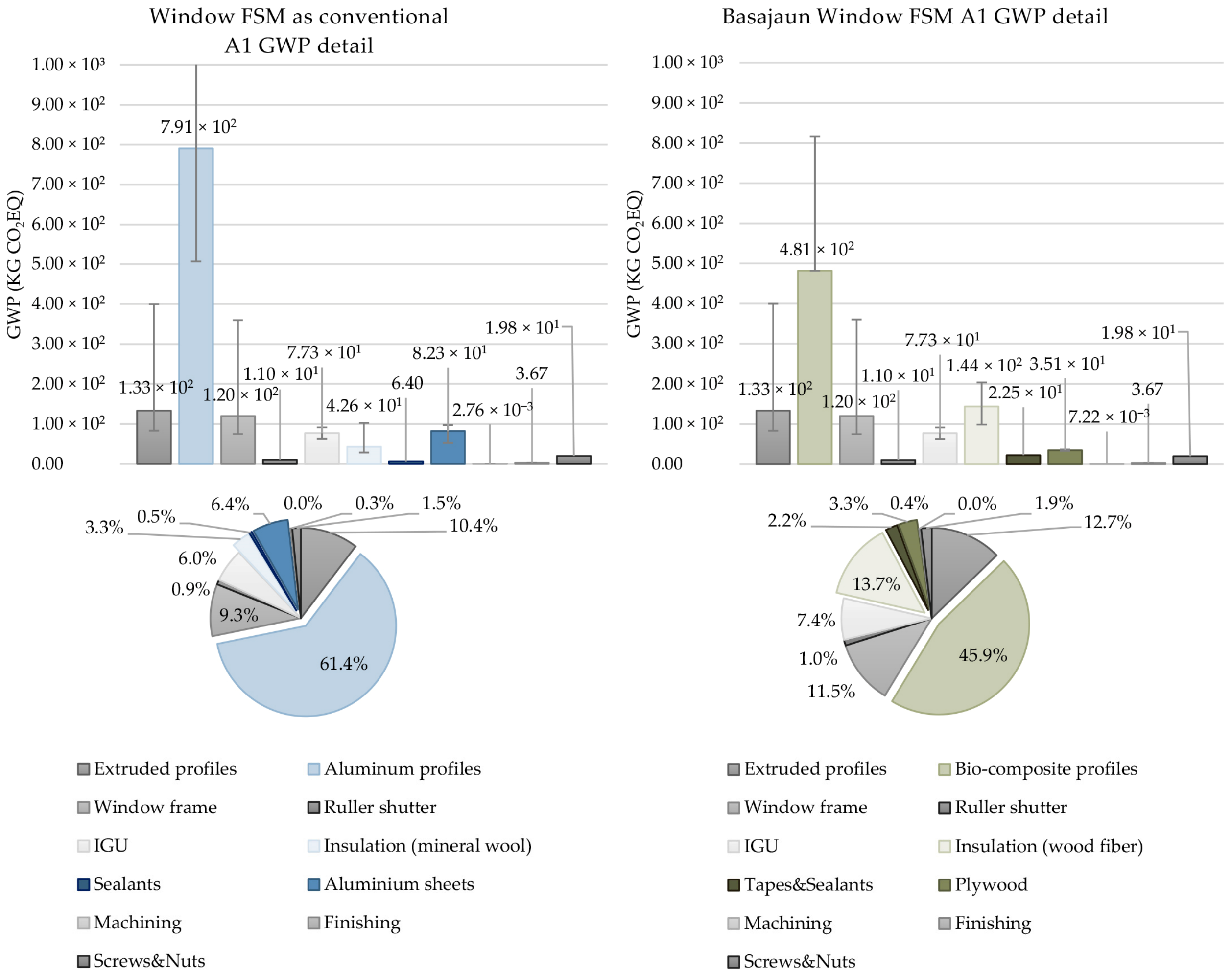


Figure 13. Comparison of the Basajaun and as-conventional Window FSM results: A1 GWP detail.

4. Discussion

This section will synthesize the key discussions about the Basajaun project objective related to Façade System Development described in the introduction. It will explore how the implementation of different façade typologies, industrialized manufacturing processes, and the use of bio-composites converge to create innovative building envelope solutions with lower emissions. The objective was to design a façade system that substitutes currently used materials with the highest wood-based and bio-composite contents while maintaining system performance and reducing carbon footprint.

Regarding the reduction in CO_2 emissions, the Embodied Carbon Assessment (ECA) performed for stages A1–A5, yielded results that align with the predicted carbon footprint reductions across all three Façade System Modules (FSMs) designed. Table 3 provides a summary of the analysis results and the corresponding percentage decrease in Global Warming Potential (GWP) for each FSM.

Table 3. Summary of the GWP reduction thanks to the Basajaun approach in the three FSMs.

	Glazed Vision FSM		Opaque FSM		Window FSM	
	$kgCO_2$/Module	$kgCO_2/m^2$	$kgCO_2$/Module	$kgCO_2/m^2$	$kgCO_2$/Module	$kgCO_2/m^2$
A1 as-conventional	1.15×10^3	2.39×10^2	8.60×10^2	1.79×10^2	1.32×10^3	2.75×10^2
A1 Basajaun	9.64×10^2	2.01×10^2	6.38×10^2	1.33×10^2	1.05×10^3	2.18×10^2
	reduction:	16%	reduction:	26%	reduction:	21%
A1, A3, and A5 as-conventional	1.16×10^3	2.41×10^2	8.72×10^2	1.82×10^2	1.33×10^3	2.77×10^2
A1, A3, and A5 Basajaun	9.75×10^2	2.03×10^2	6.50×10^2	1.35×10^2	1.06×10^3	2.20×10^2
	reduction:	16%	reduction:	25%	reduction:	21%
A1–A5 as-conventional	1.44×10^3	3.00×10^2	1.06×10^3	2.21×10^2	1.71×10^3	3.56×10^2
A1–A5 Basajaun	1.36×10^3	2.84×10^2	9.17×10^2	1.91×10^2	1.52×10^3	3.16×10^2
	reduction:	5%	reduction:	14%	reduction:	11%

The results of the ECA for these Façade System Modules revealed that the materials with the highest CO_2 emissions were the frame profiles and glass due to their quantity and characteristics, confirming the literature findings [61–63]. As a result, the modules with larger quantities of profiles, such as the Opaque FSM (with a 26% reduction in A1 GWP) and the window FSM (with a 21% reduction in A1 GWP), saw the greatest benefits from substituting critical materials with those made from forest-based and bio-composite sources. However, it is fundamental to recognize that the potential contribution of greenhouse gas emissions to global warming does not provide a comprehensive view of the overall environmental impact of an object, with other aspects like energy consumption, resource depletion, toxicity, and water footprint being essential to guarantee a broader range of environmental impact categories, giving a more holistic understanding of sustainability. To analyze these aspects, other assessments like a complete LCA would be needed. Moreover, the study delves into the A1–A5 life cycle stages, which encompass raw material extraction to façade practical completion. Developing end-of-life plans for a prototypical product is intricate, and one can only rely on assumptions based on prior knowledge.

Moving forward with the considerations of the results, a point should be made on the insulation equipment. Even though wood fiber insulation is often considered to have lower embodied carbon than mineral wool insulation [64], this analysis revealed a rise in CO_2eq emissions due to the implementation of wood fiber insulation equipment when compared to the alternative due to considering its biogenic carbon as actual emissions in A1. This could be attributed to the EPDs referenced in the analysis, which exhibited a significant variance in values based on the chosen product used as a reference. Nonetheless, when the biogenic carbon within the material is taken into account as compensation, the overall GWP of this technological system could be considered significantly reduced. It is pertinent to note that the biogenic carbon, as discussed in this study, was reported as having been emitted to the atmosphere in A1 instead of C3. This approach, if not specified, could potentially lead to misunderstandings.

The benefits of factory-based manufacturing are widely recognized, including cost efficiency, quality control, scalability, and advanced automation technologies [65,66]. Through economies of scale, factories can produce goods in large quantities, distributing fixed costs across a greater number of units and reducing the cost per module [67]. Standardized processes and automated machinery ensure consistent product quality, while scalability allows manufacturers to quickly respond to changes in demand. Incorporating prefabricated modules assembled in line is a crucial element for product sustainability. Nevertheless, in order to achieve a sustainable transition, the utmost consideration must be given to limiting the production of new materials only to cases where other, more virtuous principles of the circular economy can no longer be applied. This approach will significantly contribute to the preservation of our natural resources and help mitigate the negative impacts of industrial activities on the environment.

When it comes to pultrusion and extrusion technologies, extrusion is known for its ability to create intricate shapes and lighter profiles. This process operates within the thermoplastic domain, while pultrusion works with thermosetting materials. Extruded profiles are generally lighter, allowing for the production of more profiles from the same amount of raw material. Though pultrusion has some advantages in energy consumption per unit weight (kW/kg), with the bio-composite profile reducing energy consumption by about 70% compared to aluminum profile extrusion, it is difficult to make a direct comparison due to the fundamental differences in technology, output characteristics, and material properties. It is important to take into account that a Basajaun pultruded profile measuring one meter in length weighs nearly twice as much as an equivalent aluminum profile with comparable structural properties. Extrusion is versatile in creating complex shapes and lighter products [68], while pultrusion excels in producing stiffer and more durable profiles [35].

The considerable weight of bio-composite profiles also affects negative aspects concerning atmospheric emissions resulting from their use. Their more significant weight and cross-sections compared to conventional structures increase the impact of transporting FSMs of this type, because the mass of the load transported is directly proportional to the emissions of the transporting vehicle. Moreover, it might happen that due to its slightly larger volume, the system design causes fewer modules that can be loaded on a single truck, resulting in more trips. However, this last specific condition did not happen during the Basajaun project. Also, during the construction phase, these features require greater amounts of consumed energy and could also adversely affect the timing of the on-site installation process. The use and maintenance phase of the life cycle is also outside the domain of analysis presented in this research; however, it could have highlighted how the developed bio-composite profiles seem to require lower maintenance than metal or aluminum profiles. Despite these drawbacks, the results describe them as a lower-emission solution than a corresponding conventional profile. However, another crucial concern regarding the profiles that is not within the scope of this analysis pertains to the building's structural system. With their increased mass, these profiles may necessitate an oversizing of the load-bearing structure supporting the façade system. As the structure is a major contributor to the embodied carbon of a building [69,70], these factors could have significant implications for the GWP of the building, particularly in the case of tall structures. However, this was not evaluated in this particular presented analysis.

It was claimed already that bio-based wall panels are a first step in integrating a circular economy approach in the construction sector, using renewable resources, carbon sequestration potential, and high-quality suitability for reuse and recycling [71]. However, regarding aspects related to the circular economy, further analysis of the FSMs developed in Basajaun is necessary. While prefabrication of the modules in the factory offers advantages such as easier disassembly at the end of life, it is not yet possible to confidently state that the Basajaun's façade system is more circular than a conventional system. By examining alternative technological systems individually, it becomes clear that specific insights are required to test the recyclability of bio-composite profiles. While reuse could be evaluated only at its disposal, the fibrous materials from which it is composed would likely require at least surface treatment and may not guarantee adequate characteristics for reuse with the same function, necessitating a downcycle. Chemical recycling methods, such as conventional pyrolysis, solvent, and dissolution recycling, are viable options that aim to transform plastic waste into its original components or beneficial products [72]. These methods can be considered feasible alternatives for recycling the bio-composite profiles. Conventional pyrolysis emerges as a widespread thermal process operating in the absence of oxygen, thermally degrading the resin matrix into oil, gases, and solid products [73]. This method, typically executed between 400 °C and 700 °C, yields fibers, char on the fibers, and fillers from the solid products, offering a promising route for recycling. However, challenges include the need for high temperatures and the potential for energy-intensive processes [74]. Moreover, solvolysis, a prevalent chemical recycling process, involves dissolving the polymer matrix with chemicals like acids, bases, and solvents. While mechanically shredding and grounding solid fiber-reinforced plastic waste, solvolysis provides uniformity and higher fiber lengths without imposing high mechanical and thermal forces. However, the use of chemicals and solvent recovery steps pose challenges, environmental concerns, and process complexities. Lastly, the dissolution process introduces an innovative concept where a carefully chosen solvent selectively dissolves the polymer matrix, allowing for polymer recovery. This process, classified into superheated solvent dissolution, enables the separation of polymers from composite waste, offering energy-efficient precipitation of the polymer through flash evaporation. Each of these recycling techniques presents opportunities for the recycling of the bio-composite components, contributing to a broader approach to circular materials' management. However, the trade-offs involve chemical use, solvent recovery, and energy considerations. A careful evaluation of these methods shall contribute to a comprehensive approach to construction. Wood fiber insulation, being of organic origin, can be considered a circular material. It can be biodegradable and it can come from the recycling of waste wood from sawmills [64], but its end-of-life use options are still the subject of much scientific research. Mineral wool insulation, provided as an alternative in the proposed conventional module, can be recycled or reused, making it a sustainable alternative to current mortars made from composite materials [75]. Lastly, the sheathing and taping provided to ensure seals are composed of several layers that cannot be separated and are therefore unable to be recycled.

5. Conclusions

The presented prefabricated Façade System Modules (FSMs) developed within the Basajaun H2020 project represent a pioneering venture into incorporating bio-based materials into sustainable and operational building envelope systems, aiming to reduce the environmental impact of façade systems through innovative design, material choices, and manufacturing processes.

The comprehensive Embodied Carbon Assessment (ECA) conducted from cradle to practical completion (stages A1–A5), provided valuable insights into the environmental performance of the FSMs. Another ECA was conducted by replicating the assessment as per the same FSMs but designed as-conventional prefabricated façade modules to establish a benchmark reference for analysis. This approach provided a more comprehensive understanding of the unique design characteristics.

While some EPDs are available for certain components used in the facade modules analyzed, obtaining primary data for assessing environmental impact categories has proven difficult or even impossible. Moving forward, it is essential for the construction industry to increase the amount of data available to properly evaluate the environmental impacts of materials and components. Suppliers play a crucial role in this endeavor by raising awareness among manufacturers and purchasers, paving the way for virtuous networks in the construction industry. This approach encourages sustainable practices and promotes demand for eco-friendly materials.

The results demonstrated that substituting critical materials with forest-based and bio-composite sources can reduce CO_2 emissions. The frame profiles, identified as the primary contributors to emissions, showed significant GHG emission reductions when replaced with the pultruded bio-composite profiles developed within the project. Consequently, the Opaque FSM and Window FSM, with larger quantities of profiles, exhibited substantial reductions in A1 GWP, witnessing reductions of 26% and 21% in A1 GWP, respectively, and highlighting the potential for impactful carbon footprint reduction in façade systems.

While the benefits of reducing emissions in frame profiles were apparent, challenges arose with wood fiber insulation. The analysis revealed a rise in CO_2eq emissions compared to the mineral wool alternative, underscoring the relevance of considering biogenic carbon in the evaluation.

Factory-based manufacturing processes proved advantageous, aligning with industry-recognized benefits such as quality control and scalability. The comparison between pultrusion and extrusion technologies highlighted the need to consider each method's strengths and limitations carefully. Extrusion's versatility in creating intricate shapes and lighter profiles demonstrates advantages in specific contexts. Pultrusion proved valuable for bio-composite applications thanks to its reduced energy consumption per kg of profile (9.77×10^{-2} kWh/kg). However, the considerable weight of bio-composite profiles can introduce challenges during transportation and installation on-site. While the analysis confirmed a lower overall environmental impact than conventional alternatives, the weight considerations necessitate careful planning to mitigate potential structural implications. While further analysis is required to assess bio-composite profiles' recyclability and determine their end-of-life, there are various methods of chemical recycling, such as pyrolysis, solvent, and dissolution recycling, which have the potential to convert bio-composite material waste into its original elements or useful products.

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Data Availability Statement: The datasets analyzed during the study and openly available are in the Zenodo repository under the title: "Project Database and Environmental and Circularity Database containing information on Basajaun Façade System Modules" (DOI: https://doi.org/10.5281/zenodo.10557349).

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Conflicts of Interest: This information only reflects the author's views and neither the Agency nor the Commission are responsible for any use that may be made of the information contained herein. The authors declare that they have no financial interest or personal relationships that could have influenced the work presented in this article.

References

1. Pörtner, H.-O.; Roberts, D.C.; Poloczanska, E.S.; Mintenbeck, K.; Tignor, M.; Craig, M.; Langsdorf, S.; Löschke, S.; Möller, V.; Okem, A. IPCC, 2022: Summary for Policymakers. In *Climate Change 2022: Impacts, Adaptation and Vulnerability*; Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2022; pp. 3–33.
2. Building Research Establishment; Deloitte; Executive Agency for Small and Medium-Sized Enterprises (European Commission). Extenso Innovation Croissance. In *Study on Circular Economy Principles for Buildings' Design: Final Report*; Publications Office of the European Union: Luxembourg, 2021.
3. Ratiarisoa, R.; Magniont, C.; Ginestet, S.; Oms, C.; Escadeillas, G. Assessment of Distilled Lavender Stalks as Bioaggregate for Building Materials: Hygrothermal Properties, Mechanical Performance and Chemical Interactions with Mineral Pozzolanic Binder. *Constr. Build. Mater.* **2016**, *124*, 801–815. [CrossRef]
4. Vinod, A.; Sanjay, M.; Suchart, S.; Jyotishkumar, P. Renewable and Sustainable Biobased Materials: An Assessment on Biofibers, Biofilms, Biopolymers and Biocomposites. *J. Clean. Prod.* **2020**, *258*, 120978. [CrossRef]
5. Jones, D.; Ormondroyd, G.O.; Curling, S.F.; Popescu, C.-M.; Popescu, M.-C. 2-Chemical Compositions of Natural Fibres. In *Advanced High Strength Natural Fibre Composites in Construction*; Fan, M., Fu, F., Eds.; Woodhead Publishing: Sawston, UK, 2017; pp. 23–58. [CrossRef]
6. Leszczyszyn, E.; Heräjärvi, H.; Verkasalo, E.; Garcia-Jaca, J.; Araya-Letelier, G.; Lanvin, J.-D.; Bidzińska, G.; Augustyniak-Wysocka, D.; Kies, U.; Calvillo, A.; et al. The Future of Wood Construction: Opportunities and Barriers Based on Surveys in Europe and Chile. *Sustainability* **2022**, *14*, 4358. [CrossRef]
7. Kardung, M.; Cingiz, K.; Costenoble, O.; Delahaye, R.; Heijman, W.; Lovrić, M.; van Leeuwen, M.; M'Barek, R.; van Meijl, H.; Piotrowski, S.; et al. Development of the Circular Bioeconomy: Drivers and Indicators. *Sustainability* **2021**, *13*, 413. [CrossRef]
8. Kayaçetin, N.C.; Piccardo, C.; Versele, A. Social Impact Assessment of Circular Construction: Case of Living Lab Ghent. *Sustainability* **2022**, *15*, 721. [CrossRef]
9. Kutnik, M.; Suttie, E.; Brischke, C. 10-Durability, Efficacy and Performance of Bio-Based Construction Materials: Standardisation Background and Systems of Evaluation and Authorisation for the European Market. In *Performance of Bio-Based Building Materials*; Jones, D., Brischke, C., Eds.; Woodhead Publishing: Sawston, UK, 2017; pp. 593–610. [CrossRef]
10. Winandy, J.E.; Morrell, J.J. Improving the Utility, Performance, and Durability of Wood- and Bio-Based Composites. *Ann. For. Sci.* **2017**, *74*, 25. [CrossRef]
11. Vedernikov, A.; Gemi, L.; Madenci, E.; Onuralp Özkılıç, Y.; Yazman, Ş.; Gusev, S.; Sulimov, A.; Bondareva, J.; Evlashin, S.; Konev, S.; et al. Effects of High Pulling Speeds on Mechanical Properties and Morphology of Pultruded GFRP Composite Flat Laminates. *Compos. Struct.* **2022**, *301*, 116216. [CrossRef]
12. Vedernikov, A.; Tucci, F.; Carlone, P.; Gusev, S.; Konev, S.; Firsov, D.; Akhatov, I.; Safonov, A. Effects of Pulling Speed on Structural Performance of L-Shaped Pultruded Profiles. *Compos. Struct.* **2021**, *255*, 112967. [CrossRef]
13. Pokharel, A.; Falua, K.J.; Babaei-Ghazvini, A.; Acharya, B. Biobased Polymer Composites: A Review. *J. Compos. Sci.* **2022**, *6*, 255. [CrossRef]
14. Haraguchi, K. Biocomposites. In *Encyclopedia of Polymeric Nanomaterials*; Kobayashi, S., Müllen, K., Eds.; Springer: Berlin/Heidelberg, Germany, 2021; pp. 1–8. [CrossRef]
15. Ahmad, H.; Chhipi-Shrestha, G.; Hewage, K.; Sadiq, R. A Comprehensive Review on Construction Applications and Life Cycle Sustainability of Natural Fiber Biocomposites. *Sustainability* **2022**, *14*, 15905. [CrossRef]
16. Sunthonrvarabhas, J.; Sriroth, K.; Kim, H.-J. Polysaccharide Bio-Based Composites: Nanofiber Fabrication and Application. In *Bio-Based Composites for High-Performance Materials*; CRC Press: Boca Raton, FL, USA, 2014.
17. Li, Y.; Chen, L. Investigation of European Modular Façade System Utilizing Renewable Energy. *Int. J. Low-Carbon Technol.* **2022**, *17*, 279–299. [CrossRef]
18. Machado, N.; Morioka, S.N. Contributions of Modularity to the Circular Economy: A Systematic Review of Literature. *J. Build. Eng.* **2021**, *44*, 103322. [CrossRef]
19. Roxas, C.L.C.; Bautista, C.R.; Dela Cruz, O.G.; Dela Cruz, R.L.C.; De Pedro, J.P.Q.; Dungca, J.R.; Lejano, B.A.; Ongpeng, J.M.C. Design for Manufacturing and Assembly (DfMA) and Design for Deconstruction (DfD) in the Construction Industry: Challenges, Trends and Developments. *Buildings* **2023**, *13*, 1164. [CrossRef]
20. Fernando, D.; Navaratnam, S.; Rajeev, P.; Sanjayan, J. Study of Technological Advancement and Challenges of Façade System for Sustainable Building: Current Design Practice. *Sustainability* **2023**, *15*, 14319. [CrossRef]
21. Juaristi, M.; Sebastiani, I.; Avesani, S. Timber-Based Façades with Different Connections and Claddings: Assessing Materials' Reusability, Water Use and Global Warming Potential. *J. Façade Des. Eng.* **2022**, *10*, 71–86. [CrossRef]
22. López-Guerrero, R.E.; Vera, S.; Carpio, M. A Quantitative and Qualitative Evaluation of the Sustainability of Industrialised Building Systems: A Bibliographic Review and Analysis of Case Studies. *Renew. Sustain. Energy Rev.* **2022**, *157*, 112034. [CrossRef]
23. Final Report Summary-BIOBUILD (High Performance, Economical and Sustainable Biocomposite Building Materials.) | FP7 | CORDIS | European Commission. Available online: https://cordis.europa.eu/project/id/285689/reporting (accessed on 17 May 2023).

24. Forest Based Composites for Façades and Interior Partitions to Improve Indoor Air Quality in New Builds and Restoration | Osirys Project | Fact Sheet | FP7. CORDIS | European Commission. Available online: https://cordis.europa.eu/project/id/609067 (accessed on 30 October 2023).
25. Sposito, C.; Scalisi, F. Built Environment and Sustainability. Recycled Materials and Design for Disassembly between Research and Good Practices. *AGATHÓN Int. J. Archit. Art Des.* **2020**, *8*, 106–117. [CrossRef]
26. Savoja, G. Experimentation of Composites Materials Reinforced with Vegetable Fibres for the Construction Sector. *TECHNE-J. Technol. Archit. Environ.* **2018**, *16*, 317–324. [CrossRef]
27. Keijzer, E.E. Environmental Quickscans as a Decision Supporting Tool: Scanning the Embodied Energy of Different Fibre Treatments in the Development of Biocomposite Building Products. In *Green Design, Materials and Manufacturing Processes*; CRC Press: Boca Raton, FL, USA; Taylor & Francis Group: London, UK, 2013; pp. 113–118.
28. Arregi, B.; Garay-Martinez, R.; Astudillo, J.; García, M.; Ramos, J.C. Experimental and Numerical Thermal Performance Assessment of a Multi-Layer Building Envelope Component Made of Biocomposite Materials. *Energy Build.* **2020**, *214*, 109846. [CrossRef]
29. Astudillo, J.; González, M.G.; Sacristán, J.; Uranga, N.; Leivo, M.; Mueller, M.; Roig, I.; Langer, S.; Gemignani, G.; Vilkki, M.; et al. New Biocomposites for Innovative Construction Façades and Interior Partitions. *J. Façade Des. Eng.* **2018**, *6*, 065–083. [CrossRef]
30. BASAJAUN-Building A SustainAble Joint between rurAl and UrbaN Areas through Circular and Innovative Wood Construction Value Chains | BASAJAUN Project | Fact Sheet | H2020. CORDIS | European Commission. Available online: https://cordis.europa.eu/project/id/862942 (accessed on 20 July 2023).
31. Galán-Marín, C.; Martínez-Rocamora, A.; Solís-Guzmán, J.; Rivera-Gómez, C. Natural Stabilized Earth Panels versus Conventional Façade Systems. Economic and Environmental Impact Assessment. *Sustainability* **2018**, *10*, 1020. [CrossRef]
32. Proposal for a Directive of the European Parliament and of the Council on the Energy Performance of Buildings (Recast). 2021. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021PC0802&qid=1641802763889 (accessed on 18 January 2024).
33. CWCT Embodied Carbon Committee. Sustainability Guide 01: An Introduction to Sustainability in Façades; Centre for Window and Cladding Technology: The Studio, Entry Hill, Bath, BA2 5LY. 2021, pp. 1–62. Available online: https://www.visionarch.co.uk/sites/default/files/2021-12/CWCT_Sustainability_Guide_01.pdf (accessed on 21 December 2023).
34. Paoletti, I.; Nastri, M. The Typology of the Mullions and Transoms Façade System. In *Executive Design of the Façade Systems: Typologies and Technologies of the Advanced Building Envelopes*; Paoletti, I., Nastri, M., Eds.; SpringerBriefs in Applied Sciences and Technology; Springer Nature: Cham, Switzerland, 2023; pp. 29–52. [CrossRef]
35. Vedernikov, A.; Safonov, A.; Tucci, F.; Carlone, P.; Akhatov, I. Pultruded Materials and Structures: A Review. *J. Compos. Mater.* **2020**, *54*, 4081–4117. [CrossRef]
36. *UNE-EN ISO 527-4:1997*; Plastics—Determination of Tensile Properties—Part 4: Test Conditions for Isotropic and Orthotropic Fibre-Reinforced Plastic Composites. ISO: Geneva, Switzerland, 1997.
37. *UNE-EN ISO 14126:2001+AC:2002*; Fibre-Reinforced Plastic Composites—Determination of Compressive Properties in the in-Plane Direction (ISO 14126:1999/Cor.1:2001). ISO: Geneva, Switzerland, 1997.
38. Torres, J.; Garay-Martinez, R.; Oregi, X.; Torrens-Galdiz, J.I.; Uriarte-Arrien, A.; Pracucci, A.; Casadei, O.; Magnani, S.; Arroyo, N.; Cea, A.M. Plug and Play Modular Façade Construction System for Renovation for Residential Buildings. *Buildings* **2021**, *11*, 419. [CrossRef]
39. PEFC-Programme for the Endorsement of Forest Certification. Available online: https://www.pefc.org/ (accessed on 15 December 2023).
40. *EN 1602:2013*; Thermal Insulating Products for Building Applications—Determination of the Apparent Density. European Committee For Standardization: Brussels, Belgium, 2013.
41. *EN 13171:2012+A1:2015*; Thermal Insulation Products for Buildings—Factory Made Wood Fibre (WF) Products—Specification. European Committee For Standardization: Brussels, Belgium, 2015.
42. *EN 12667:2002*; Thermal Performance of Building Materials and Products—Determination of Thermal Resistance by Means of Guarded Hot Plate and Heat Flow Meter Methods—Products of High and Medium Thermal Resistance. Slovenian Institute for Standardization: Ljubljana, Slovenia, 2002.
43. Tokuç, A.; Özkaban, F.F.; Çakır, Ö.A.; Tokuç, A.; Özkaban, F.F.; Çakır, Ö.A. Biomimetic Façade Applications for a More Sustainable Future. In *Interdisciplinary Expansions in Engineering and Design with the Power of Biomimicry*; IntechOpen: Rijeka, Croatia, 2018. [CrossRef]
44. Ladipo, T.; Wild, W. How to Calculate Embodied Carbon of Façades: A Methodology; CWCT Embodied Carbon Committee, Series Ed.; Centre for Window and Cladding Technology: The Studio, Entry Hill, Bath, BA2 5LY. 2022, pp. 1–62. Available online: https://www.cwct.co.uk/pages/embodied-carbon-methodology-for-fa%C3%A7ades (accessed on 21 December 2023).
45. *ISO EN 14040:2006*; Environmental Management-Life Cycle Assessment Principles and Framework. ISO: Geneva, Switzerland, 2006.
46. *ISO EN 14044:2006*; Environmental Management-Life Cycle Assessment Requirements and Guidelines. ISO: Geneva, Switzerland, 2006.
47. Dams, B.; Maskell, D.; Shea, A.; Allen, S.; Cascione, V.; Walker, P. Upscaling Bio-Based Construction: Challenges and Opportunities. *Build. Res. Inf.* **2023**, *51*, 764–782. [CrossRef]

48. *EN 15804:2012+A2:2019/AC:2021*; Sustainability of Construction Works-Environmental Product Declarations-Core Rules for the Product Category of Construction Products. CEN-CENELEC Management Centre: Brussels, Belgium, 2021.
49. *EN 15978:2011*; Sustainability of Construction Works-Assessment of Environmental Performance of Buildings-Calculation Method. CEN-CENELEC Management Centre: Brussels, Belgium, 2011.
50. European Aluminium. *Environmental Profile Report: Life-Cycle Inventory Data for Aluminium Production and Transformation Processes in Europe*; Avenue de Broqueville 12; European Aluminium: Brussels, Belgium, 2018. Available online: https://european-aluminium.eu/wp-content/uploads/2022/10/european-aluminium-environmental-profile-report-2018-executive-summary.pdf (accessed on 21 December 2023).
51. European Composites Industry Association (EuCIA). Eco Impact Calculator for Composited V1.1.1. Zurich, Switzerland. 2023. Available online: https://ecoinvent.org/the-ecoinvent-database/data-releases/ecoinvent-3-7-1/ (accessed on 1 December 2023).
52. Azrague, K.; Inman, M.R.; Alnæs, L.-I.; Schlanbusch, R.D.; Jóhannesson, B.; Sigfusson, T.I.; Thorhallsson, E.R.; Franzson, H.; Arnason, A.B.; Vares, S. Life Cycle Assessment as a Tool for Resource Optimisation of Continuous Basalt Fibre Production in Iceland. In *Life Cycle Assessment and Other Assessment Tools for Waste Management and Resource Optimization*; ECI Symposium Series; ECI: New York, NY, USA, 2016.
53. Ecoinvent Association. Ecoinvent V3.7.1 | Synthetic Rubber. Zurich, Switzerland. 2020. Available online: https://ecoinvent.org/the-ecoinvent-database/data-releases/ecoinvent-3-7-1/ (accessed on 1 December 2023).
54. Ecoinvent Association. Ecoinvent V3.7.1 | Powder Coat, Steel. Zurich, Switzerland. 2020. Available online: https://ecoinvent.org/the-ecoinvent-database/data-releases/ecoinvent-3-7-1/ (accessed on 1 December 2023).
55. Ecoinvent Association. Ecoinvent V3.7.1 | Transport, Freight, Lorry EURO5 {RER} Avg 3 to >32 Metric Tons. Zurich, Switzerland. 2020. Available online: https://ecoinvent.org/the-ecoinvent-database/data-releases/ecoinvent-3-7-1/ (accessed on 1 December 2023).
56. Joshi, S.; Chen, X. Time-Variant Simulation of Multi-Material Thermal Pultrusion. *Appl. Compos. Mater.* **2011**, *18*, 283–296. [CrossRef]
57. Jeswani, A.; Roux, J. Modeling of Processing for Slot and Discrete Port Tapered Resin Injection Pultrusion. *J. Thermophys. Heat Transf.* **2008**, *22*, 749–757. [CrossRef]
58. Breton, C.; Blanchet, P.; Amor, B.; Beauregard, R.; Chang, W.-S. Assessing the Climate Change Impacts of Biogenic Carbon in Buildings: A Critical Review of Two Main Dynamic Approaches. *Sustainability* **2018**, *10*, 2020. [CrossRef]
59. Hydro Aluminium, AS. Hydro 75R Aluminium Extrusion Ingot (EPD), The Norwegian EPD Foundation: Oslo, Norway, 2019. NEPD-1841-768-EN. Available online: https://www.hydro.com/globalassets/download-center/certificates/nepd-1841-768-hydro-75r-aluminium-extrusion-ingot.pdf (accessed on 21 December 2023).
60. Ecoinvent Association. Ecoinvent V3.8 (Consequential) | 4153: Semi-Finished Products of Aluminium or Aluminium Alloys. 2021. Available online: https://ecoinvent.org/the-ecoinvent-database/data-releases/ecoinvent-3-8/ (accessed on 1 December 2023).
61. Taborianski, V.M.; Prado, R.T.A. Methodology of CO_2 Emission Evaluation in the Life Cycle of Office Building Façades. *Environ. Impact Assess. Rev.* **2012**, *33*, 41–47. [CrossRef]
62. Kim, K.-H. A Comparative Life Cycle Assessment of a Transparent Composite Façade System and a Glass Curtain Wall System. *Energy Build.* **2011**, *43*, 3436–3445. [CrossRef]
63. Soler, D.; Salandin, A.; Bevivino, M. Using Integer Linear Programming to Minimize the Embodied CO_2 Emissions of the Opaque Part of a Façade. *Build. Environ.* **2020**, *177*, 106883. [CrossRef]
64. Densley Tingley, D.; Hathway, A.; Davison, B. An Environmental Impact Comparison of External Wall Insulation Types. *Build. Environ.* **2015**, *85*, 182–189. [CrossRef]
65. Mkrkdtth, J.R.; Surksh, N.C. Justification Techniques for Advanced Manufacturing Technologies. *Int. J. Prod. Res.* **1986**, *24*, 1043–1057. [CrossRef]
66. Sjödin, D.R.; Parida, V.; Leksell, M.; Petrovic, A. Smart Factory Implementation and Process Innovation. *Res.-Technol. Manag.* **2018**, *61*, 22–31. [CrossRef]
67. Adel, A. Future of Industry 5.0 in Society: Human-Centric Solutions, Challenges and Prospective Research Areas. *J. Cloud Comput.* **2022**, *11*, 40. [CrossRef]
68. Qamar, S.Z.; Chekotu, J.C.; Al-Maharbi, M.; Alam, K. Shape Complexity in Metal Extrusion: Definitions, Classification, and Applications. *Arab. J. Sci. Eng.* **2019**, *44*, 7371–7384. [CrossRef]
69. Li, S.; Yan, H.; Chen, J.; Shen, L. A Life Cycle Analysis Approach for Embodied Carbon for a Residential Building. In Proceedings of the 20th International Symposium on Advancement of Construction Management and Real Estate, Hangzhou, China, 23–25 October 2015; Wu, Y., Zheng, S., Luo, J., Wang, W., Mo, Z., Shan, L., Eds.; Springer: Singapore, 2017; pp. 1185–1196. [CrossRef]
70. Vilčeková, S.; Čuláková, M.; Burdová, E.K.; Katunská, J. Energy and Environmental Evaluation of Non-Transparent Constructions of Building Envelope for Wooden Houses. *Energies* **2015**, *8*, 11047–11075. [CrossRef]
71. Cascione, V.; Roberts, M.; Allen, S.; Dams, B.; Maskell, D.; Shea, A. Life Cycle Assessment of Circular Bio-Based Construction. *Constr. Technol. Archit.* **2022**, *1*, 124–134. [CrossRef]
72. Gharde, S.; Kandasubramanian, B. Mechanothermal and Chemical Recycling Methodologies for the Fibre Reinforced Plastic (FRP). *Environ. Technol. Innov.* **2019**, *14*, 100311. [CrossRef]

73. Singh, R.K.; Ruj, B.; Sadhukhan, A.K.; Gupta, P. Conventional Pyrolysis of Plastic Waste for Product Recovery and Utilization of Pyrolytic Gases for Carbon Nanotubes Production. *Environ. Sci. Pollut. Res.* **2022**, *29*, 20007–20016. [CrossRef]
74. Kooduvalli, K.; Unser, J.; Ozcan, S.; Vaidya, U.K. Embodied Energy in Pyrolysis and Solvolysis Approaches to Recycling for Carbon Fiber-Epoxy Reinforced Composite Waste Streams. *Recycling* **2022**, *7*, 6. [CrossRef]
75. Piña Ramírez, C.; Atanes Sánchez, E.; del Río Merino, M.; Viñas Arrebola, C.; Vidales Barriguete, A. Feasibility of the Use of Mineral Wool Fibres Recovered from CDW for the Reinforcement of Conglomerates by Study of Their Porosity. *Constr. Build. Mater.* **2018**, *191*, 460–468. [CrossRef]