



Article

A Comparative Environmental and Economic Analysis of Carbon Fiber-Reinforced Polymer Recycling Processes Using Life Cycle Assessment and Life Cycle Costing

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Abstract: The recycling of carbon-fiber reinforced polymers (CFRPs) presents significant challenges due to their thermosetting matrix, which complicates end-of-life management and often results in energy-intensive disposal or significant waste accumulation. Despite advancements in recycling methods, knowledge gaps remain regarding their sustainability and economic viability. This study undertakes a comprehensive Life Cycle Assessment and Environmental Life Cycle Costing analysis of four key recycling techniques: mechanical recycling, pyrolysis, solvolysis, and high-voltage fragmentation (HVF). By using the SimaPro software, this study identifies mechanical recycling and HVF as the most sustainable options, with the lowest cumulative energy demand (CED) of 5.82 MJ/kg and 4.97 MJ/kg and global warming potential (GWP) of 0.218 kg CO₂eq and 0.0796 kg CO₂eq, respectively. In contrast, pyrolysis imposes the highest environmental burdens, requiring 66.3 MJ/kg and emitting 2.84 kg CO₂eq. Subcritical solvolysis shows more balanced environmental impacts compared to its supercritical counterpart. Cost analysis reveals that for mechanical recycling and pyrolysis, material costs are negligible or zero. In contrast, solvolysis and HVF incur material costs primarily due to the need for deionized water. Regarding energy costs, pyrolysis stands out as the most expensive method due to its high energy demands, followed closely by solvolysis with supercritical water.

Keywords: carbon fiber-reinforced polymers recycling; recycling processes comparison; life cycle assessment of CFRP; life cycle costing of CFRP



Academic Editor: Yong X. Gan

Received: 22 December 2024

Revised: 10 January 2025

Accepted: 12 January 2025

Published: 15 January 2025

Citation: Vogiantzi, C.; Tserpes, K. A Comparative Environmental and Economic Analysis of Carbon Fiber-Reinforced Polymer Recycling Processes Using Life Cycle Assessment and Life Cycle Costing. *J. Compos. Sci.* **2025**, *9*, 39. <https://doi.org/10.3390/jcs9010039>

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1. Introduction

CFRPs have become increasingly popular in engineering because of their excellent strength-to-weight ratio, stiffness, corrosion resistance, and overall mechanical, thermal, and chemical properties [1,2]. The potential for weight reduction, which results in reduced fuel use and major environmental advantages, is a major factor in this shift toward CFRP [3]. Despite the performance benefits of thermoset composites, recyclability remains a significant barrier, particularly as these materials approach the end of their life cycle. Thermoset composites are not biodegradable and, unlike thermoplastics, cannot be melted and reshaped into new products [4]. Although waste management has been a priority in the European Union in recent decades [5], a lot of composite waste still ends up in landfills or incinerated [6]. For years, landfill and incineration have been the main disposal methods, but both have significant disadvantages: landfilling contributes to waste accumulation, while incineration consumes large amounts of energy [7].

To protect the environment, stricter legislation and economic initiatives are needed to encourage more sustainable recycling practices for composite materials [4]. This has led to the development of three main recycling techniques for CFRPs: mechanical, thermal, and chemical recycling. The mechanical recycling process involves crushing, shredding, and milling CFRP components into smaller fragments and then grinding them into a fine powder. One of the primary advantages of mechanical recycling is that it generally requires less energy than other recycling technologies, helping to lower also the cost [8]. Thermal recycling, especially pyrolysis, has the ability to recover carbon fibers without the need for chemical solvents [9]. While thermal recycling is effective for fiber recovery, additional oxidation steps may sometimes be required to improve fiber quality [10]. Chemical recycling, or solvolysis, involves using a solvent to separate fibers from the matrix. This process uses various solvents applied at high pressure and temperature to break down the polymer matrix [11,12]. A significant advantage of solvolysis is the recovery of valuable fibers and residual chemicals [13,14]. A recent innovative alternative for recycling CFRP that utilizes their electrical properties is high-voltage fragmentation [15].

Despite advancements, recycling CFRPs remains challenging due to the high energy demands and the variability in the quality of recovered materials [16,17]. Scientific and applied problems include the lack of efficient recycling technologies that effectively balance cost and environmental impact, as well as the limited integration of recycled materials back into high-value applications [18,19]. The motivation of recycling thermoset polymer composites is also driven by the high cost of producing virgin fibers and the need to address environmental issues [20]. Recycling solutions aim to reduce CFRP materials' financial and environmental costs [21]. Furthermore, Life Cycle Assessment (LCA) has proven valuable for decision-making, providing insight into environmental [22] and cost impacts. The environmental effects of recycling technologies have also been explored across various material systems. Refs. [23,24] emphasize the importance of integrating LCA in evaluating the sustainability of emerging recycling solutions. Similarly, ref. [25] demonstrates how LCA and Life Cycle Costing (LCC) can be used to assess the feasibility of recycling technologies. The evaluation of environmental and cost impacts of CFRP recycling processes in particular has been studied by many authors: mechanical recycling [26,27], pyrolysis [28–30], solvolysis [29,31], and high voltage fragmentation [32,33]. Additionally, other studies have compared and evaluated various recycling methods based on their environmental and/or economic performance, highlighting differences and benefits among them. For instance, ref. [34] assessed the environmental and economic feasibility of several CFRP waste management methods, including grinding, pyrolysis, microwave, and supercritical water recycling. By using LCA and LCC, this study compared the effectiveness of these processes in recovering carbon fibers and reducing global warming potential (GWP). Furthermore, ref. [35] examined recycling processes like pyrolysis, fluidized bed, and chemical recycling, demonstrating significant reductions in GWP and primary energy demand (PED) compared to landfill and incineration, with GWP reductions between 19 and 27 kg CO₂eq and PED savings from 395 to 520 MJ per kg CFRP. Ref. [36] compared the environmental impacts of pyrolysis and solvolysis using supercritical water. The findings showed that solvolysis offers no significant gains over pyrolysis in terms of environmental and human health impacts. Finally, ref. [37] carried out a comparison of end-of-life scenarios, such as landfilling and incineration, with recycling technologies like pyrolysis, supercritical solvolysis, and electrodynamic fragmentation, showing that while recycling generally has a higher energy demand, it becomes environmentally advantageous when the substitution of virgin products is considered.

Nevertheless, there are still many critical gaps in current research. While individual recycling methods have been widely studied, few comparative evaluations examine both

environmental and economic issues. Finally, many recycling methods remain economically inefficient due to the high energy requirements and cost of the materials. Comprehensive LCC analyses are needed to identify cost reduction opportunities and enhance the economic viability of these technologies. In this study, the environmental and economic impacts of CFRP recycling will be addressed utilizing the LCA and LCC approach using SimaPro 9.6.01 software to evaluate four recycling processes: mechanical recycling, pyrolysis, solvolysis (with supercritical and subcritical water as a solvent), and high-voltage fragmentation. The aim of this study is (i) to quantify and compare the environmental impacts of selected recycling methods using cumulative energy consumption and global warming potential over a 100-year horizon and (ii) to assess the life cycle costs associated with each recycling process to provide a view of their economic feasibility.

2. Life Cycle Assessment and Life Cycle Costing Methodology

According to ISO 14040 and 14044 [38,39], LCA is the process of gathering and evaluating a product system's inputs, outputs, and environmental impacts during its entire life cycle. LCA consists of four phases [40]:

1. **Goal and Scope Definition:** This stage establishes the study's objectives. Key methodological decisions are also determined here, such as defining the functional unit, setting system boundaries, identifying impact categories, and selecting Life Cycle Impact Assessment (LCIA) models.
2. **Life Cycle Inventory (LCI):** This phase collects data and calculates system inputs and outputs. Data gathering includes foreground operations (such as manufacturing and packing) and background processes (such as the production of bought power and materials).
3. **Life Cycle Impact Assessment:** This phase connects LCI data with environmental impact categories and indicators. LCIA methods categorize emissions into impact categories and quantify them into equivalent units, allowing for a more accurate evaluation of ecological impacts.
4. **Life Cycle Interpretation:** The final phase aligns the outcomes of LCI and LCIA with the purpose and scope. This stage comprises checking for completeness, sensitivity, and consistency.

LCC is an assessment tool of all costs associated with a product across its whole life cycle. Environmental Life Cycle Costing (eLCC) is designed to enhance an environmental Life Cycle Assessment (eLCA) by addressing the economic aspects of a product or a process. LCC is aligned with LCA, following the same structured steps throughout the analysis. This study will use eLCA and eLCC to assess each CFRP recycling method's environmental and economic effects.

2.1. Goal and Scope Definition

The goal of this work is to assess and compare the environmental impacts and life cycle costs of four different recycling processes (mechanical recycling, pyrolysis, solvolysis (supercritical and subcritical water), and high-voltage fragmentation) for CFRP, with a baseline comparison to the production of CFRP from virgin carbon fibers (vCFs). The functional unit is defined as 1 kg of CFRP waste. The CFRP plate used in this study was manufactured in the facilities of the Hellenic Aerospace Industry and consisted of 8 plies. They were made with CYTEC PRISM EP2400 epoxy resin (Cytec Engineered Materials, Östringen, Germany) and TENAX-E IMS65 E23 24K carbon fabric (SAERTEX GmbH & Co. KG, Saerbeck, Germany). The fiber volume fraction was 70.5%, and each ply was 0.22 mm thick. The total amount of the CFRP manufactured was 1 kg. A cradle-to-grave life cycle model is chosen to assess the impacts. This approach includes all phases, from

raw material extraction (cradle) to the final disposal or end-of-life treatment (grave). The processes are assumed to take place in Europe, according to the geographical relevance of the data sources. The analysis relies on data collected during experiments and the manufacturing stage, supplemented by information from the ecoinvent database and relevant literature. The LCA and LCC are carried out using SimaPro 9.6.01 software. Categories of impacts, such as global warming potential and cumulative energy demand, are considered. Transport is excluded from the analysis as an assumption, and, therefore, transport-related impacts are not considered in the LCA and LCC.

2.2. Life Cycle Inventory

2.2.1. Production of Carbon Fiber-Reinforced Polymers

The initial step is the production of vCFs. This procedure begins with synthesizing acrylonitrile (AN) through the ammoxidation of propylene, known as the Sohio process. This process is well-documented in the ecoinvent database. Polyacrylonitrile (PAN) is synthesized through the polymerization of AN, including up to 5% by weight of co-monomers such as methyl acrylate or itaconic acid [41]. The polymer is then dissolved in a solvent, typically dimethylformamide (DMF) [42]. For every kilogram of CF produced, approximately 0.61 kg of DMF is required, with a reuse efficiency of 99%. The production of PAN fibers requires energy inputs, primarily in the form of electricity and steam. These requirements for the production of PAN fibers are detailed by [43,44]. The spinning stage includes stretching and washing the fibers, followed by a sizing step. During sizing, approximately 10% by weight of protective silicone, primarily polydimethylsiloxane (PDMS), is applied to complete the PAN fiber production [43]. The inventory data for producing 1 kg of PAN are summarized in Table 1.

Table 1. Life cycle inventory for the production of 1 kg PAN.

Input	Quantity
Acrylonitrile	0.95 kg
Methyl acrylate	0.05 kg
Dimethylformamide solvent	0.0061 kg
Polydimethylsiloxane	0.1 kg
Electric energy	66.87 MJ
Steam	18 kg

The transformation from PAN to carbon fiber involves additional stages: oxidation (stabilization), carbonization, surface treatment, and sizing, ensuring the final material's mechanical properties and surface compatibility for applications (Figure 1). The precursor fibers are stabilized by heating in an oxidizing atmosphere, which induces chemical changes to make them thermally stable. The stabilized fibers are then heated in an inert nitrogen atmosphere, where non-carbon atoms are removed, increasing carbon content to 93–95%. The carbonized fibers undergo treatment to roughen the surface and introduce functional groups, enhancing adhesion to matrix resins [45]. The final step is the sizing. Therefore, a protective coating is applied to the fibers to facilitate handling and improve compatibility with the matrix resin [46]. An epoxy sizing of 1.3% by weight was considered, as specified in the carbon fiber datasheet.

A weight ratio of 1.724 between the required PAN input and the obtained CF was assumed based on [19]. From these processes occurs the life cycle inventory for the production of virgin carbon fibers as illustrated in Figure 2. These data are derived from [37]. Background processes are modeled using the ecoinvent database, while the production of PAN is based on the description provided earlier.

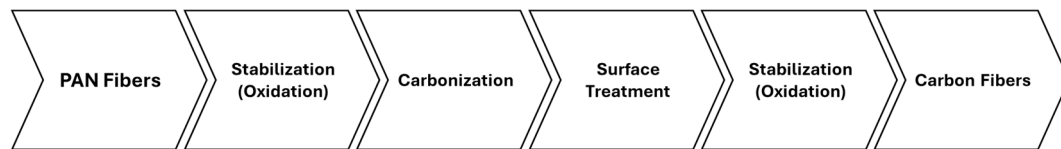


Figure 1. Schematic representation of the stages involved in the transformation of PAN fibers into carbon fibers.

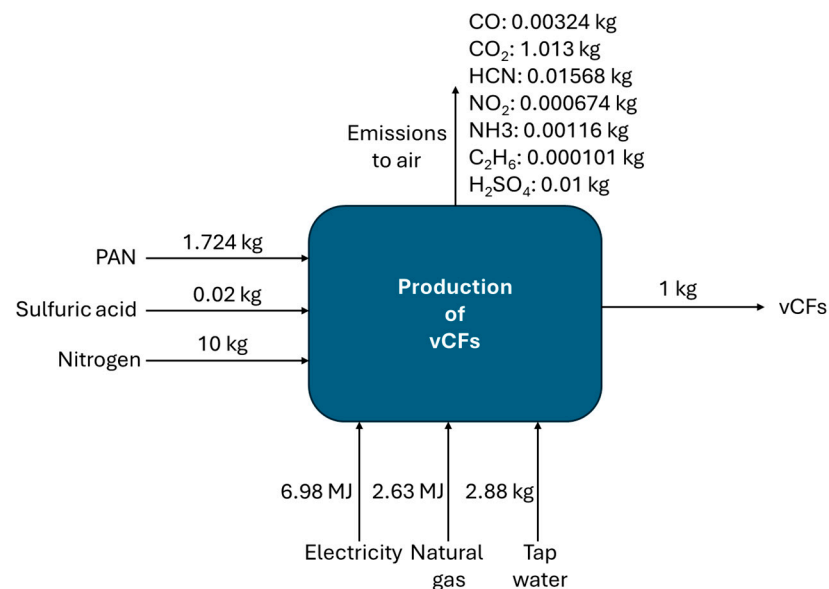


Figure 2. Life cycle inventory for the production of virgin fibers.

The typical electricity consumption for unidirectional (UD) production is calculated to be approximately 0.48 MJ/kg, based on data provided by [47]. The UD carbon fabric used in this study incorporates a binder, which is used to stabilize the fabric layers during handling and impregnation in liquid composite molding (LCM) processes. Binders, typically based on epoxy, polyester, or other compatible resins, play a critical role in enhancing the compression, stability, and permeability of preforms [48]. The binder is assumed to be low-density polyethylene (LDPE), with data derived from the ecoinvent database.

The PRISM EP2400 epoxy resin is a single-component, toughened liquid epoxy system. It offers both flexibility in processing and the damage tolerance required for high-performance composite structures, such as aerospace applications. However, for this study, the life cycle modeling will assume that the epoxy resin is represented by the production process documented in the ecoinvent database. This involves the reaction of bisphenol-A and epichlorohydrin in the presence of a sodium hydroxide catalyst, reflecting a common industrial practice for commercial epoxy resin manufacturing. Furthermore, the epoxy resin used in this study includes a small amount of polyethersulfone (PES) copolymer to improve the performance characteristics. However, due to the minimal PES content and for simplification in LCA, the environmental impacts are approximated based on the data for the epoxy resin only, without explicitly considering the PES.

The CFRP was fabricated using the Liquid Resin Infusion (LRI) process. In this process, dry carbon fabric is placed in a vacuum environment, and liquid resin is infused under controlled pressure. This method allows the exact resin distribution, minimizing voids and optimizing the material's mechanical properties [49]. The energy consumption for LRI (or vacuum-assisted resin injection (VARI), a similar technique), is approximately 10.2 MJ/kg of composite produced [50]. Figure 3a,b shows the preparation and the final CFRP plate, respectively.

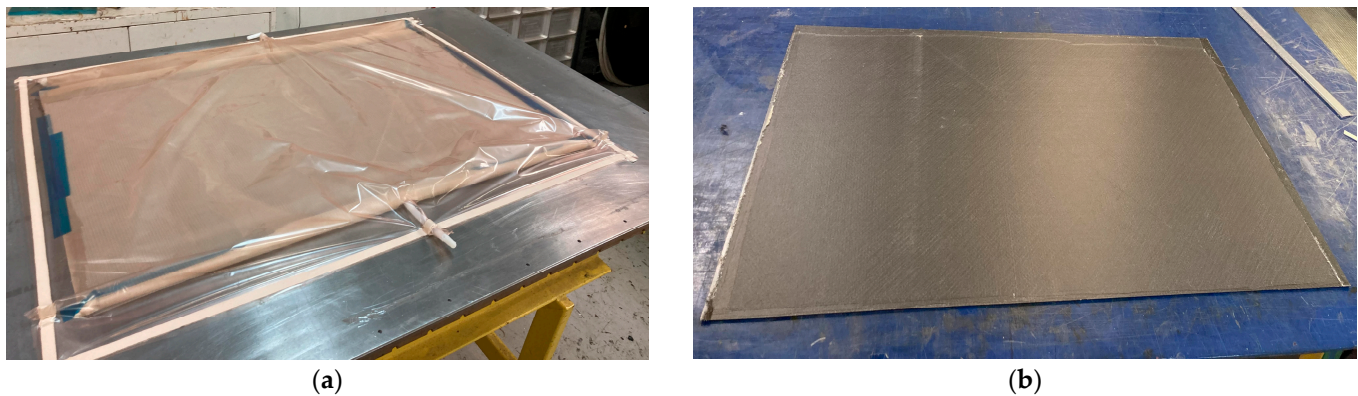


Figure 3. (a) Preparation for the LRI process. (b) Final CFRP plate, demonstrating the completed structure after fabrication.

Also, several consumables are required to support the LRI process. These include vacuum bags, peel ply, infusion mesh (resin flow media), tacky tape (sealant tape), as well as components like aspiration tubes, valves, vacuum hoses, and spiral tubing. These consumables, supplied by Easy Composites, are essential for creating the vacuum environment necessary for the LRI. For LCA, representative materials for these consumables were identified from the ecoinvent database, as shown in Table 2. The quantities of these materials were carefully recorded during the manufacturing of the CFRP plate. It is important to note that consumables used in the manufacturing stage are considered waste after use. It is also assumed that there are no material losses or wastes, such as scraps or excess resin, generated during the manufacturing process.

Table 2. Representation of consumables with materials and processes (selected from the ecoinvent database).

Product	Material
Vacuum bag	Nylon 6-6
Peel ply	Polyethylene terephthalate, granulate
Infusion mesh	Polypropylene, granulate
Tacky tape	Synthetic rubber
Aspiration tubes	Nylon 6-6
Vacuum hose	Polypropylene, granulate
Valves, spiral tubing, etc.	Polypropylene, granulate

2.2.2. End-of-Life Processes—Recycling Processes

Mechanical recycling. Mechanical recycling of composites focuses on reducing the size of waste components for reuse in new materials [51]. The recycling process typically starts with a primary crushing phase, where CFRPs are reduced in size to pieces about 50–100 mm. The next step involves secondary grinding, carried out using hammer mills or high-speed mills, which reduces the material into finer particles, generally ranging from 10 mm to under 50 μm [4,52]. The output of the recycling process consists of 24 wt% fine fibers, 19 wt% fine powders, and 57 wt% coarse recyclate [53]. The fine fibers can be repurposed as reinforcement in new composite materials by partially replacing raw fiber. However, there is a limit to the amount of rCF that can be used before the mechanical properties of the composite begin to degrade significantly [4]. Material losses are common during the mechanical recycling of CFRP waste. Typically, about 10% of the original CFRP waste input is lost, mainly due to the steps of size reduction and grinding. The total energy demand for CFRP recycling in this process involves two stages: shredding and mechanical milling. The shredding stage requires 0.27 MJ/kg, while the next stage of mechanical milling has

an energy demand of 2.03 MJ/kg based on [26]. This calculation for grinding is based on industrial grinding with a feed hopper with a processing rate of 10 kg/h. Figure 4 provides a detailed flowchart of the mechanical recycling process.

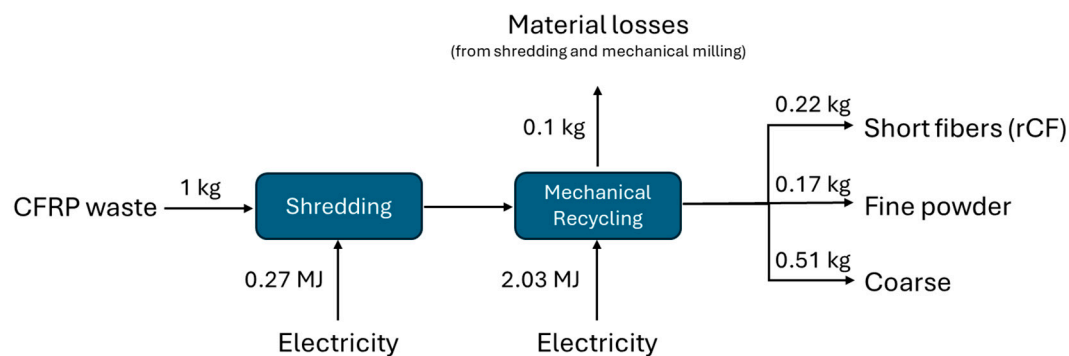


Figure 4. Flowchart of the mechanical recycling process.

Pyrolysis. Pyrolysis is a widely studied thermal recycling process for composites, where materials are heated in the absence or presence of oxygen and, more recently, in steam [11]. This method breaks down the resin matrix into oils, gases, and solid residues, including fibers that may require cleaning to remove char [54]. Post-treatment at high temperatures (450–1300 °C) can effectively clean the fibers but risks degrading their mechanical properties. Carbon fibers retain better properties depending on the pyrolysis conditions, balancing resin removal and fiber integrity [55]. The CFRP waste is first shredded using a mechanical mill using energy requirements data based on [26]. Pyrolysis, a thermal decomposition process, occurs in the absence of oxygen or with controlled oxygen flow at temperatures between 300 °C and 800 °C. Nitrogen is also used to prevent the oxidation of carbon fibers. Gases from resin degradation are collected, while solid residues (char) are usually disposed of in landfills. Energy consumption for recovering 1 kg of carbon fiber is estimated at approximately 30 MJ, producing rCF, ash, and emissions to the air [56]. The LCI data are from [35] with nitrogen input referenced from [57]. Figure 5 provides the flowchart.

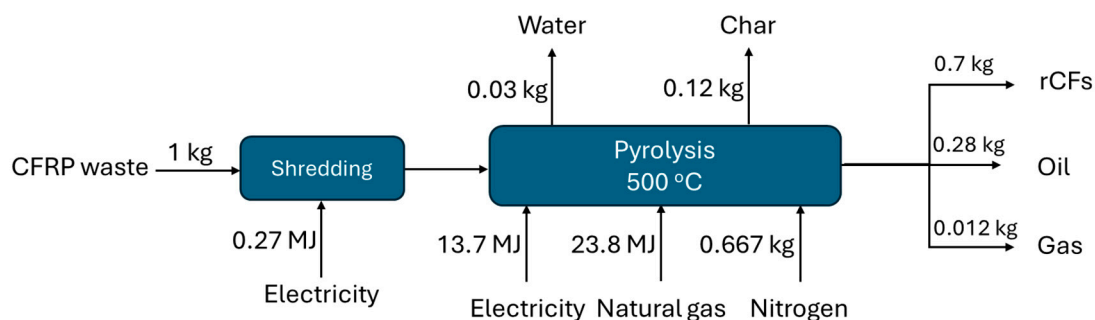


Figure 5. Flowchart of the pyrolysis process.

Solvolytic. Chemical recycling involves the depolymerization of polymer matrices using specific chemical solvents. This process recovers clean fibers and matrix material, which can be transformed into monomers or petrochemical feedstocks. Known as solvolysis, the method varies by solvent type, including hydrolysis (water), glycolysis (glycols), etc. High temperatures and pressures are often applied under subcritical or supercritical conditions for faster, more efficient dissolution [58]. The experimental setup involved a high-pressure, high-temperature reactor, where CFRP samples were treated with supercritical and subcritical water. The solvent was chosen for its environmental benefits, availability, and low toxicity [59]. In this process, CFRP waste is placed in the reactor

without pre-shredding, as the reactor size is designed to accommodate the desired fiber length. Water is pressurized to about 250 bars for supercritical water and 170 bars for subcritical water. The temperatures are 380 °C and 350 °C, respectively. Water consumption is approximately 10 L/kg of CFRP [37]. Energy requirements are calculated based on the water's heat capacity. To determine the energy required to heat the water, considering that heat capacity is not constant [60], the equation is expressed as follows:

$$Q = m \int_{T_1}^{T_2} c_p dT. \quad (1)$$

Here, Q is the energy required (J), m is the mass of water (kg), T_1 is the ambient temperature in °C, T_2 is the desired temperature of the experiment in °C, and c_p is the heat capacity (J/kg°C), which varies with temperature. This integral accounts for the changing value of c_p between 20 °C and 380 °C for the supercritical solvolysis and between 20 °C and 380 °C for the subcritical solvolysis. After calculating the energy requirements (approximately) for both supercritical and subcritical solvolysis, the results are presented in Figure 6a,b, respectively. These figures illustrate the input and output flows of each process. In this study, it is assumed that all water used during the solvolysis process is treated as waste, with no evaporation considered. Additionally, the entire quantity of the epoxy matrix is considered resin waste, as its recovery or reuse is not included within the scope of this analysis.

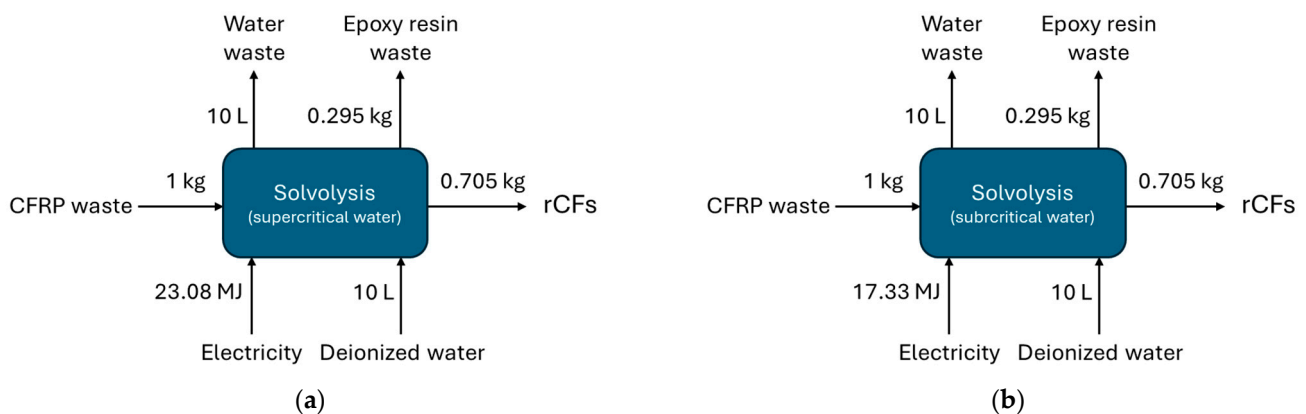


Figure 6. Flowchart of the solvolysis process (a) with supercritical water and (b) with subcritical water.

High Voltage Fragmentation. High-voltage fragmentation (HVF) is a recycling process that uses electrical discharges to break down materials. High-voltage pulses are generated by a Marx generator, creating plasma channels in a water-filled vessel between electrodes [61]. These plasma channels produce intense energy, high pressures, and shock waves, leading to cracks and fragmentation in the material, especially in weaker components [62]. Water is the dielectric medium due to its low cost, availability, and environmental advantages [61]. The process decomposes the materials through repeated pulses, eventually fragmenting the CFRP. The process for high-voltage shredding recycling starts by shredding the CFRP waste into smaller pieces. These shreds are processed in a high-voltage fragmentation system, where deionized water acts as a dielectric medium. During the process, nitrogen is used to create the optimal conditions for effective fragmentation. Afterward, the treated material undergoes filtration to separate and recover the fragmented CFs for further utilization. The filters used can be reused; therefore, they are excluded from consideration in the LCA and LCC. The data for this HVF process are based on findings from the study conducted by [37], which details the energy consumption, operational parameters, and mass balance. The HVF recycling process is illustrated in Figure 7.

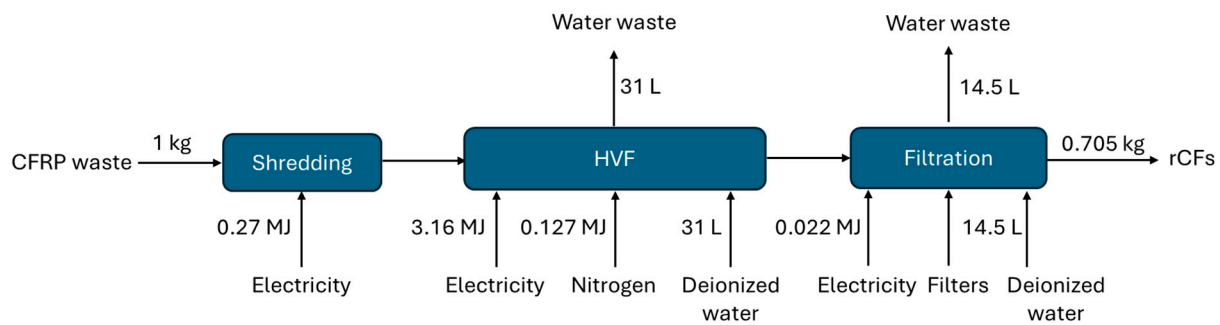


Figure 7. Flowchart of the HVF recycling process.

In some recycling processes, such as solvolysis, the fibers require cleaning and oven drying to eliminate humidity. However, the consumption of water or solvents such as acetone for cleaning and the energy consumption of the drying oven are not included in the calculation.

2.3. Life Cycle Impact Assessment

In this study, the environmental impacts and costs of recycling CFRP waste and the production of CFRP are assessed using the SimaPro 9.6.01 software with the ecoinvent 3 database. The analysis focuses on four recycling methods: mechanical recycling, pyrolysis, solvolysis (subcritical and supercritical water), and HVF. The methods selected for LCA are Cumulative Energy Demand (CED), IPCC 2021 GWP100, and ReCiPe Endpoint. These methodologies enable the comprehensive assessment of energy use, climate change potential (in kg CO₂-eq over a 100-year horizon), and endpoint-level damage to ecosystems, human health, and resource depletion. Each recycling method is assessed within the context of its environmental performance across these metrics.

For the LCC analysis, the method proposed by SimaPro was developed. This approach includes economic data within the LCA framework to evaluate the costs associated with the different recycling processes and CFRP production. The methodology includes cost categories such as operational costs, which cover energy and material costs, and integrates them into the life cycle stages to provide an economic assessment.

3. Results

The final phase of LCA is the interpretation of the results. This phase evaluates the findings from the LCI and LCIA stages, providing an analysis of the environmental impacts of the studied scenarios. This is followed by the LCC, where the economic aspects of the same scenarios are assessed. Below, the interpretation of the results is presented.

3.1. Interpretation of Life Cycle Assessment Results

After completing the LCA, the CED for producing 1 kg of vCFs was calculated to be 747 MJ, while the GWP was determined to be 34.3 kg CO₂-eq. A detailed breakdown of the most significant environmental impacts during the production process of vCFs is provided in Figure 8. This figure does not represent the overall tree diagram of the process but highlights the key stages contributing to the environmental burden. The thickness of the red lines in the diagram indicates the relative magnitude of environmental impacts of each process stage. Among these, the production of PAN is identified as the most environmentally intensive step. This is largely attributed to its substantial electricity demand (115 MJ) and the extensive use of chemical inputs such as acrylonitrile (1.64 kg) and polydimethylsiloxane (0.172 kg). Afterward, we evaluate the manufacturing of the CFRP plate with consumables using the LRI technique. The CED method is applied to analyze the electricity consumption for CFRP production, and the GWP is calculated to

assess the carbon footprint of the process. The CED analysis (Figure 9) indicates that the production of vCFs has the highest impact on energy consumption. For this calculation, average electricity consumption data for Europe were used. However, it is important to note that this amount is likely to vary in different geographical areas due to differences in energy sources and efficiency.

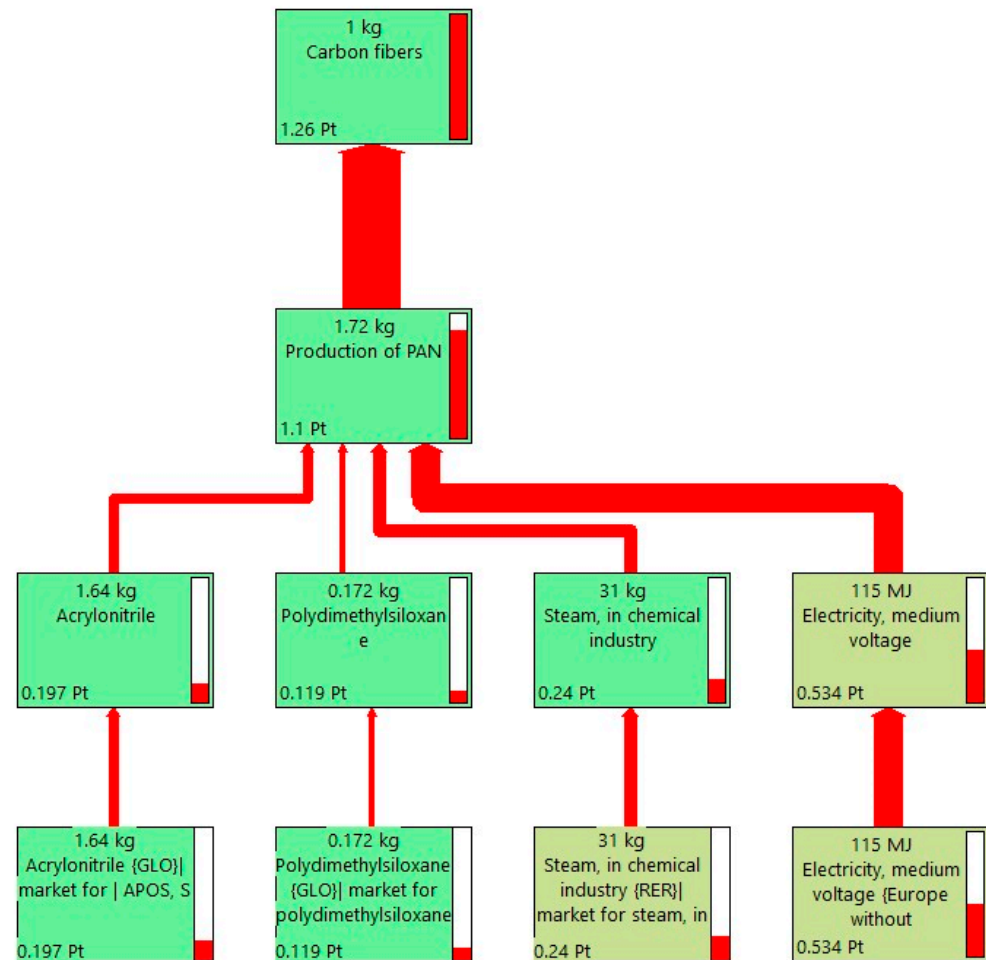


Figure 8. Tree diagram of the production of virgin fibers.

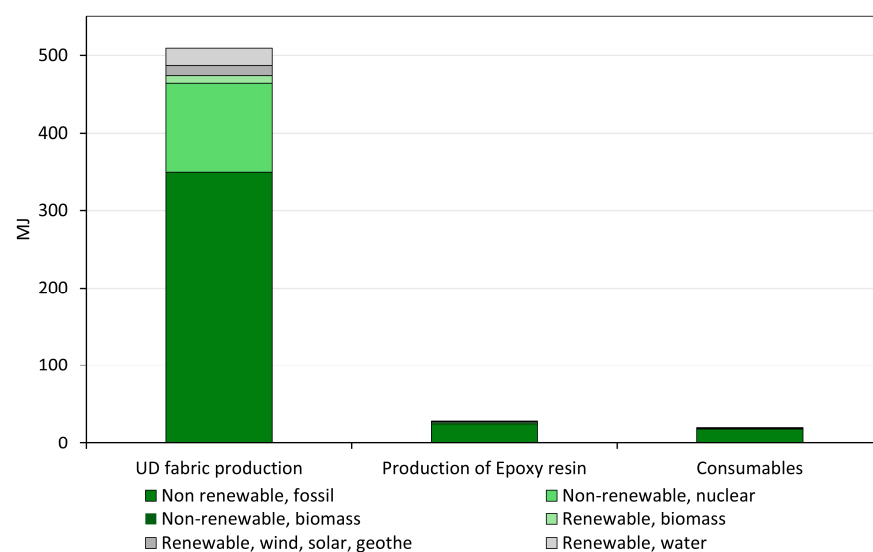


Figure 9. CED for the manufacturing process of CFRP plate.

The total GWP is 25.2 kg CO₂eq, comprising:

- 23.3 kg CO₂eq from UD fabric production, reflecting the high impact of the carbon fiber production stage,
- 1.31 kg CO₂eq from epoxy resin production, and
- 0.624 kg CO₂eq from consumables such as vacuum bags.

A breakdown of the energy sources reveals that non-renewable, fossil-based energy is the predominant contributor to this stage, followed by smaller contributions from renewable sources such as, wind, solar, and water, with an almost negligible contribution from biomass. The high dependence on fossil fuels for energy highlights a critical opportunity for improvement by transitioning to cleaner energy sources.

Also, an evaluation of the damage assessment using the Recipe Endpoint method is depicted in Figure 10. The results highlight the relative contributions of CFRP and consumables to environmental impacts, measured in points (Pt). It is important to note that the waste of consumables category does not contribute to the environmental impact in this analysis, as the waste is simply considered as discarded material with no further treatment applied, such as landfill. The impacts are categorized into the following three areas: human health, ecosystems, and resources. The main impact is due to the manufacturing of CFRP itself, which significantly outweighs the contribution of consumables and waste. A closer look at the results indicates that the most significant environmental burden lies in the human health category, primarily due to the energy-intensive process of CFRP production. This includes the high-energy requirements for carbon fiber manufacturing and the use of chemical inputs, which contribute to emissions that directly or indirectly affect human well-being. Ecosystem impacts and resource depletion are also observed but to a lower degree compared to the human health category. This outcome emphasizes the critical role of optimizing CFRP manufacturing processes to mitigate its environmental footprint.

To enable the comparison of the recycling methods, Table 3 presents the CED and GWP values for each process. Only the impacts of energy requirements and materials used during recycling processes are considered. Energy consumption associated with waste treatment, such as wastewater or epoxy resin waste management and potential energy recovery, is excluded. Including these factors could reveal potential energy gain or revenue from energy recovery. Therefore, the focus remains on the energy inputs and material use during recycling processes.

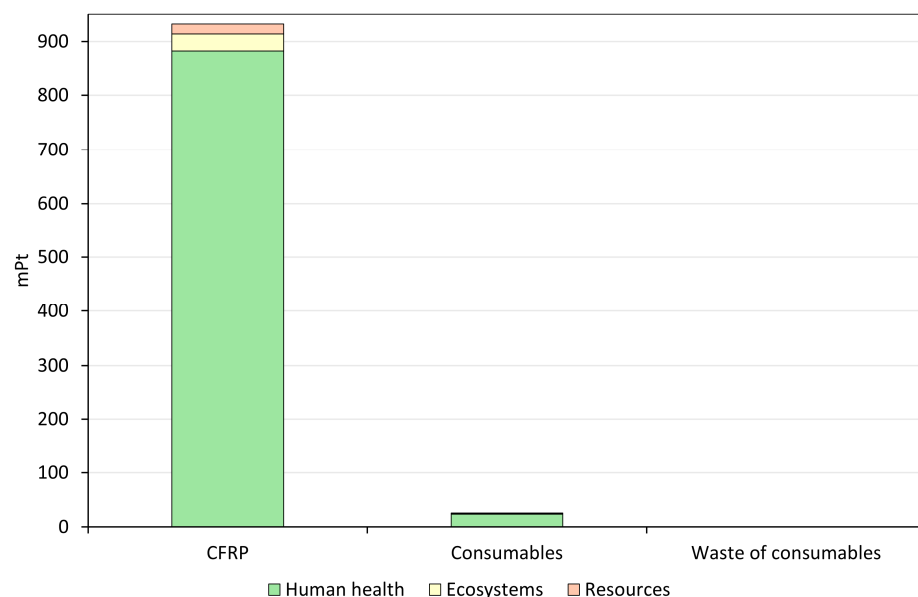


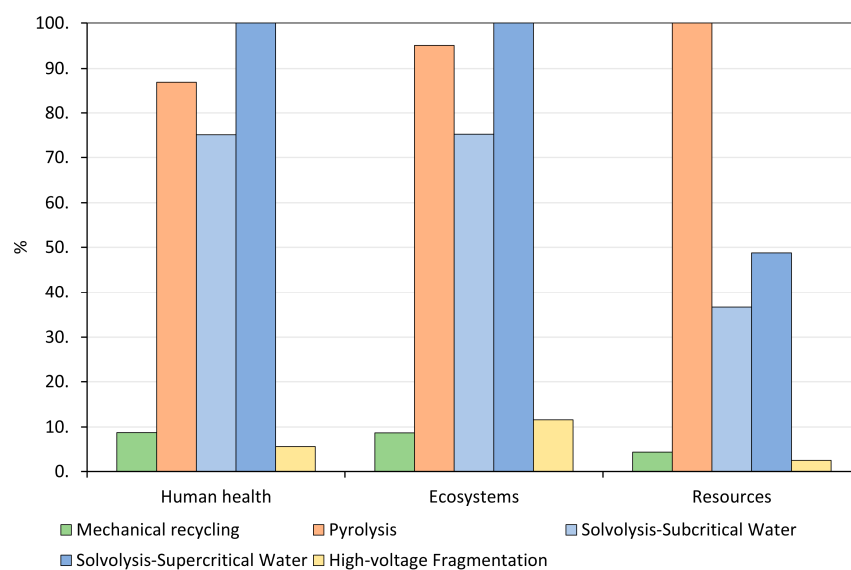
Figure 10. Damage assessment of CFRP production using Recipe Endpoint.

Table 3. CED and GWP of recycling for recycling processes.

Recycling Process	CED (MJ/kg CFRP Waste)	GWP (kg CO ₂ eq/kg CFRP Waste)
Mechanical recycling	5.82	0.218
Pyrolysis	66.3	2.84
Solvolysis-subcritical water	49.8	1.87
Solvolysis-supercritical water	66.3	2.49
HVF	4.97	0.0796

Recycling processes have significantly lower energy consumption and carbon footprints compared to vCFs production. Among the recycling methods, mechanical recycling and HVF exhibit the lowest CED and GWP values, primarily due to their minimal energy requirements. In contrast, pyrolysis and supercritical water solvolysis require substantial energy inputs, with pyrolysis relying on natural gas and solvolysis needing high energy to surpass the critical point of water and reach the required 380 °C temperature for processing. Additionally, an evaluation of the damage assessment using the Recipe Endpoint method for the different recycling methods is presented (Figure 11). This evaluation categorizes the environmental impacts into the following three key areas: human health, ecosystems, and resources. Mechanical recycling and HVF show minimal impacts in all categories, benefiting human health and resources in particular. Their simple processes avoid the need for high temperatures or extensive use of chemical agents, making them sustainable options for recycling. In contrast, pyrolysis and solvolysis with supercritical water have significant negative effects on human health and ecosystems. Pyrolysis, in particular, has significant environmental impacts, especially in terms of resources. Solvolysis with subcritical water, however, has more balanced environmental impacts.

These findings underline the importance of selecting appropriate recycling technologies based on specific environmental priorities. Mechanical recycling and HVF are ideal for scenarios prioritizing resource efficiency and low environmental impact. Conversely, pyrolysis and solvolysis may require further optimization to reduce their environmental footprint, especially in regions where energy production is dependent on fossil fuels.

**Figure 11.** Comparison of the damage assessment of the recycling processes.

3.2. Life Cycle Costing Results

In the LCC, only material and energy costs are considered. The country of material production is considered; however, transportation costs are excluded from the analysis.

Material costs are obtained from suppliers selling these materials, while energy costs are based on the average energy price in Europe [63]. The LCC data inventory for materials and energy costs associated with manufacturing CFRP plate is detailed in Table 4, with costs presented in EUR/kg for each input. It accounts for the total cost of producing carbon fiber, epoxy resin, and consumables. These costs are relatively high, as the calculation is based on the production of a single kilogram rather than mass production, where economies of scale would reduce costs. Additionally, the analysis considers raw material and energy costs, not the market price of finished products like carbon fiber. After calculations, the total cost for producing 1 kg of CFRP is EUR 211.

Table 4. LCI of costs for materials and energy for the production of CFRP.

Input	Impact Category	Factor	Unit
UD production	Material costs	246	EUR/kg
Epoxy resin	Material costs	100	EUR/kg
Consumables	Material costs	16.5	EUR/kg
Electricity	Energy costs	0.052	EUR/MJ

For the recycling processes, only the material and energy costs associated with the operational aspects of the methods were considered. These include the inputs and energy consumed during the recycling stages. However, potential revenue from recycled carbon fibers (rCFs) could also be factored in (not included in this analysis). If the quality and mechanical properties of the recycled fibers are sufficient, they can be reused. This could offset part of the recycling costs. As a result, reusing recycled fibers can contribute positively to the overall economic viability of the processes. In Figure 12, the material and energy costs for each recycling process are displayed, offering a detailed overview of the costs associated with each method. In mechanical recycling and pyrolysis, the material costs are either negligible or zero. However, for solvolysis and HVF, the primary material cost comes from deionized water. Regarding energy costs, pyrolysis stands out with the highest cost due to its significant energy demands. Solvolysis with supercritical water follows, as it requires considerable energy to heat the water to 380 °C. The total cost for each recycling process is as follows: mechanical recycling costs 0.106 EUR/kg CFRP waste; pyrolysis costs 4.66 EUR/kg; solvolysis with subcritical water costs 50.9 EUR/kg; solvolysis with supercritical water costs 51.2 EUR/kg; and HVF costs 155 EUR/kg.

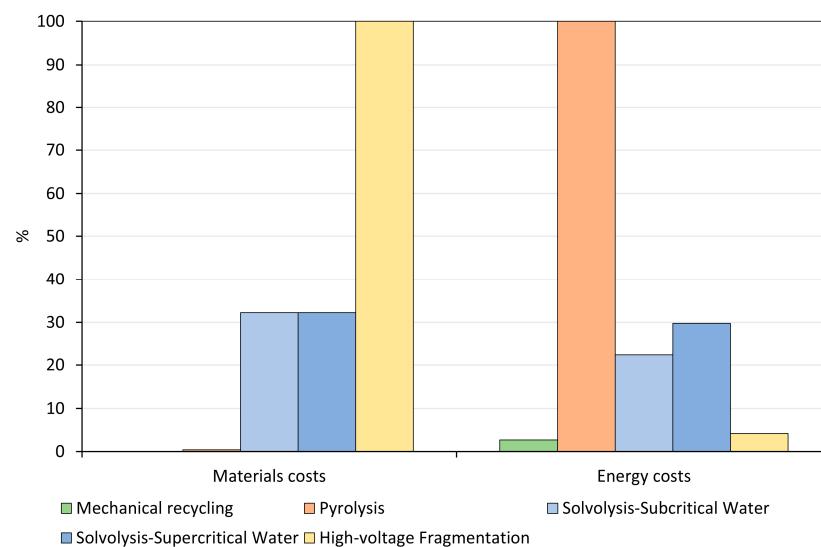


Figure 12. Comparison of materials and energy costs of the recycling processes.

This analysis highlights that selecting a recycling method must balance economic considerations with environmental impacts. While mechanical recycling is the most affordable option, its application may depend on the desired quality and properties of the recycled fibers. Solvolysis methods, despite their higher cost, may be more suitable for applications requiring high-quality recycled fibers.

4. Discussion

This paper discusses four recycling methods for CFRP, including the three main recycling methods and one innovative approach (HVF). When assessing these methods, it is important to consider both environmental impacts and cost factors such as capital and operational costs. However, the quality of the recycled fibers also plays a critical role—if the quality of the fibers is poor, recycling may not be viable. The variations in the mechanical properties of recycled fibers resulting from different recycling methods are critical for evaluating their suitability for specific applications. For instance, mechanical recycling produces lower-quality fibers, suitable primarily for non-structural components, while pyrolysis and solvolysis recover fibers with higher mechanical performance. High-quality recycled fibers may allow their use in structural applications, which could reduce the overall environmental impact across the product's life cycle [11,56]. Future studies should quantify these performance variations and incorporate them into the environmental and economic analysis.

In addition, the technology readiness levels of these methods (TRL) vary. Mechanical recycling and pyrolysis are at a high TRL, which makes them ready for use on an industrial scale, while the other methods are still in the laboratory scale phase [64]. This difference highlights the challenge of scaling up recycling processes from small samples or parts to complete structures.

One of the promising avenues for future research is the further development and optimization of chemical recycling, particularly solvolysis, which remains an evolving field. This method allows for a diverse selection of process parameters, including temperature, pressure, and reaction time [65], which must be optimized to balance mechanical properties, environmental impact, and cost efficiency. Furthermore, ongoing advancements in nanotechnology, such as the use of nano-silica or nanomodifications, could enhance the quality and mechanical properties of recycled CFRPs. Studies on nano-silica-modified asphalt binders [66] and nano-enhanced CFRP in structural reinforcements [67] indicate that such approaches can significantly enhance material performance. This opens new possibilities for recycled CFRPs to match or overcome the properties of the virgin material. However, assessing the long-term impact of using recycled CFRPs in applications is equally important. Products with non-optimal mechanical properties may result in increased material usage, shorter lifespans, or the need for additional reinforcement, potentially offsetting the carbon footprint savings achieved during recycling.

There is potential for integrating energy recovery mechanisms into the recycling processes to reduce their overall energy consumption and improve their economic feasibility.

Practical implications of this study would be relevant to industries utilizing CFRP in large-scale applications. The recycling methods developed, particularly mechanical and pyrolysis recycling, could be implemented in existing recycling facilities to improve sustainability. Furthermore, optimizing these methods for specific types of CFRP materials, as the choice of resin could influence the efficiency and the environmental impacts of the recycling process.

One significant advantage of this study is the comparison of various recycling methods for CFRPs, considering environmental impacts and cost factors. The examination of both traditional methods (mechanical and pyrolysis) and emerging techniques (such as HVF

and solvolysis) provides a wider perspective on the potential for sustainable recycling in CFRP applications.

Nonetheless, there are several limitations to this study. A strong limitation is the assumption that fibers are perfectly recycled and resin-free, which is often not the case in real-world scenarios. Additional cleaning steps are often required, contributing to environmental and economic costs that are difficult to quantify.

Another limitation is that only the costs of materials and energy used in the recycling processes have been considered in this study. Potential costs or revenues associated with waste, recycled fibers, and possible energy recovery from these processes have not been included. The integration of these factors could provide a more complete estimate of total costs. For instance, ref. [68] categorizes costs into dismantling, transportation, operation, and capital and presents a fuzzy logic-based system for estimating the recycling costs of CFRPs. Depending on the perspective of this study, recycling methods could be evaluated as a service, with the cost of providing this service being included in the analysis.

Last but not least, the most important limitation of this study is that the LCI data used for the assessment comes from various sources, including literature, experiments, and industry reports. As a result, variations in materials and energy inputs across recycling methods could influence the results. Therefore, a more reliable comparison of recycling processes would require the use of the same material (CFRP) and quantity across all methods. Additionally, input and energy requirements should be consistently calculated for each process to ensure an accurate assessment of their environmental impacts and operational costs.

In conclusion, while this study provides useful information on the current state of CFRP recycling methods, further research is needed to address the limitations and explore the integration of new technologies and recycling innovations to make these processes more efficient and scalable.

5. Conclusions

This paper evaluates the production of vCFs and the manufacturing of CFRPs using the LRI method. Additionally, it compares three conventional CFRP recycling methods—mechanical recycling, pyrolysis, and solvolysis—alongside an innovative approach, HVF. A comprehensive cost analysis of material and energy requirements accompanies these comparisons.

The LCA results reveal that mechanical recycling is the most environmentally friendly and cost-effective method, with a CED of 5.82 MJ/kg and GWP of 0.218 kg CO₂eq. HVF also performs well environmentally, with a CED of 4.97 MJ/kg and a GWP of 0.0796 kg CO₂eq, but it incurs higher costs due to its complex infrastructure. Conversely, pyrolysis and solvolysis require significantly higher energy inputs, with pyrolysis consuming 66.3 MJ/kg and emitting 2.84 kg CO₂eq, while supercritical solvolysis consumes 66.3 MJ/kg and emits 2.49 kg CO₂eq. Nevertheless, preserving carbon fiber mechanical properties should be incorporated into future assessments, ensuring the alignment of environmental and economic analyses with fiber reuse potential.

From a practical engineering point of view, mechanical recycling and HVF are particularly promising due to their low environmental impact and the possibility of integration into existing recycling facilities. Mechanical recycling offers cost advantages as it eliminates material costs and provides recycled fibers suitable for less demanding applications such as non-structural automotive components. HVFs, although currently expensive, have potential for high-value applications if their scalability is improved. Pyrolysis, despite its high energy demands, is highly effective for recovering clean carbon fibers with minimal residue. Additionally, the gases and oils generated as by-products during the pyrolysis

process can be utilized for energy recovery, which has the potential to improve the overall economic feasibility of the method.

Solvolysis, on the other hand, is capable of producing high-quality carbon fibers and recovering valuable chemical by-products. These characteristics make it suitable for demanding applications. However, the economic viability of solvolysis is currently limited by the high costs associated with solvents and energy consumption. Enhancing process efficiency and scaling up production could significantly improve the practicality of this method for industrial applications. This study is limited by assumptions such as complete resin decomposition, which may impact accuracy. Future research should aim to standardize CFRP across recycling methods, investigate energy recovery opportunities, and examine factors influencing the quality of the recycled fibers and the reuse potential.

Author Contributions: Conceptualization, C.V. and K.T.; methodology, C.V. and K.T.; software, C.V.; validation, C.V. and K.T.; investigation, C.V.; resources, K.T.; data curation, C.V.; writing—original draft preparation, C.V. and K.T.; writing—review and editing, C.V. and K.T.; visualization, C.V.; supervision, K.T.; project administration, K.T.; funding acquisition, K.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: All data are presented in the manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CFRPs	Carbon Fiber-Reinforced Polymers
EoL	End-of-Life
LCA	Life Cycle Assessment
eLCC	Environmental Life Cycle Costing
LCC	Life Cycle Costing
GWP	Global Warming Potential
PED	Primary Energy Demand
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
eLCA	Environmental Life Cycle Assessment
vCFs	Virgin Carbon Fibers
AN	Acrylonitrile
PAN	Polyacrylonitrile
DMF	Dimethylformamide
PDMS	Polydimethylsiloxane
UD	Unidirectional
LCM	Liquid Composite Molding
LDPE	Low-Density Polyethylene
PES	Polyethersulfone
LRI	Liquid Resin Infusion
VARI	Vacuum-Assisted Resin Injection
HVF	High-Voltage Fragmentation
CED	Cumulative Energy Demand
Pt	Points
rCFs	Recycled Carbon Fibers
TRL	Technology Readiness Level

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