A comparative life cycle assessment of virgin and waste carbon fiber for composite applications

Executive Summary:

This comparative LCA analyzes the environmental impacts of carbon fiber production using two systems: one relying on 100% virgin raw materials (cradle-to-gate) and the other processing 100% waste carbon fiber (gate-to-gate). The study quantifies emissions in CO_2 equivalents (CO_2eq) for 1 kg of carbon fiber used in composite applications, providing actionable insights for Omnia Products, LLC and its customers.

The results demonstrate that processing waste carbon fiber significantly reduces emissions, cutting global warming potential by 79%. Virgin fiber production results in 29.30 kg CO_2eq per kg of material, while waste fiber processing generates just 6.15 kg CO_2eq. This difference stems from the classification of waste fiber as a secondary material, with environmental burdens allocated to the original virgin fiber production. Transportation contributes 96% of emissions in the waste system, whereas electricity and energy consumption contribute the majority of emissions in the virgin fiber system.

The findings highlight the substantial environmental benefits of adopting waste material in composite applications. While the study's scope excludes certain factors (e.g., disposal of consumables and specific gaseous emissions from downstream manufacturing processes), the reduction in emissions highlights Omnia Products' ability to deliver low-impact solutions to its customers.

1. Goal and Scope

1.1 Goals

This comparative LCA will determine the environmental impacts of manufacturing and processing carbon fiber from either 100% raw or 100% waste material for composite applications. This study will be conducted to understand the environmental impacts of carbon fiber production and whether the use of waste material is more environmentally beneficial. The results of this study will be made available to Omnia Products, LLC and their customers for internal and/or public use.

1.2 Scope

1.2.1 Product system and function

- *Product:* Carbon fiber used in composite applications
- *Product system:* Two systems are included in the study:
    - System one: A cradle-to-grate system including raw material extraction, carbon fiber manufacturing, and transportation to end users.
    - System two: A gate-to-gate system including waste carbon fiber transportation, carbon fiber processing, and transportation to customers.
- *Function:* Composite applications
- *Functional unit:* 1 kg of carbon fiber used in a composite application
- *Reference flow:* 2.1 kg of polyacrylonitrile (PAN) is used to produce 1 kg of carbon fiber.

1.2.2 System boundaries

1.2.2.1 System Boundary 1

The first system boundary is a cradle-to-gate analysis of the production and distribution of 1kg of virgin carbon fiber. It includes raw materials used in acrylonitrile (AN) production, transportation of AN to PAN and carbon fiber manufacturing site, polymerization of acrylonitrile to polyacrylonitrile, carbon fiber manufacturing, and transportation to the end customer. Only energy and electricity requirements are considered AN and PAN manufacturing steps, while carbon fiber production considers additional gaseous emissions resulting from loss of material upon conversion. End use and post-life impacts are not included within the system boundary.

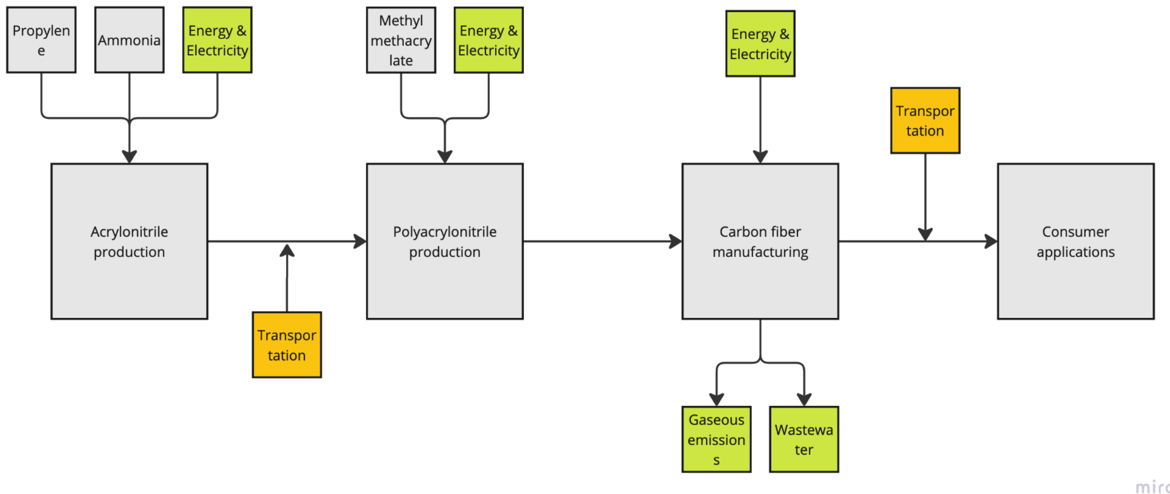

Figure 1- System Boundary 1

1.2.2.2 System Boundary 2

The second system boundary under study is a gate-to-gate analysis of waste carbon fiber processing and distribution. The system includes waste material transportation from the supplier to Omnia Products, transportation and use of consumables in the operations, the operations at Omnia Products to process the material, and the transportation to the end user. End-use and post-life impacts are not included in the system boundary. Additionally, impacts associated with the production of the waste fiber are excluded from the system since the waste fiber is not a primary product.

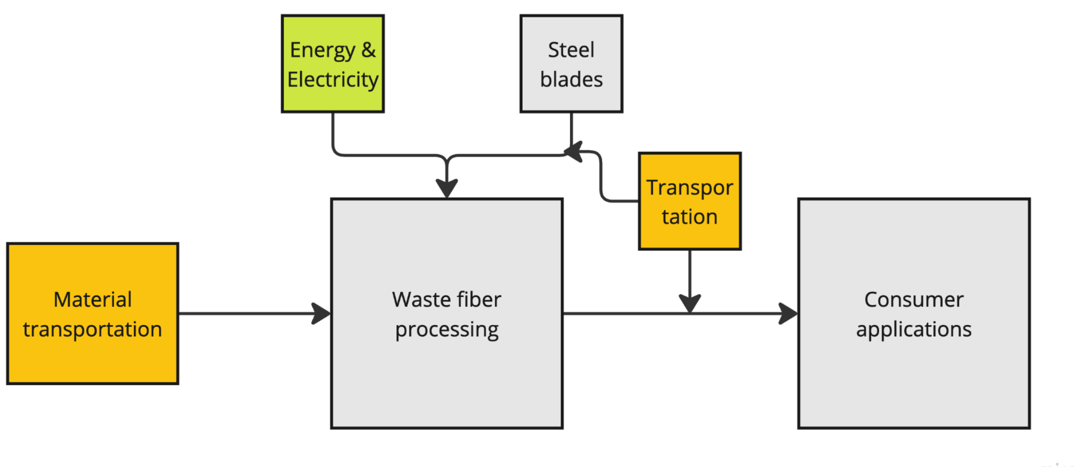

Figure 2- System Boundary 2

1.2.2.3 System Boundary Comparison Considerations

End-use and post-life impacts are not included in either system boundary. End-use and post-life impacts are equivalent in both systems under study since all impact differences will result from downstream activities. This study employs the cut-off approach for waste materials, defined by ISO 14044:2006 Clause 4.3.4.2, which classifies waste products as post-industrial waste (secondary products). Therefore, all associated environmental burdens are allocated to the primary product, the virgin carbon fiber.

2. Life Cycle Inventory Analysis

2.1 Acrylonitrile Production

Acrylonitrile (AN) is produced by the ammoxidation of propylene (Sohio process). AN production data was obtained from a 2019 Argonne National Laboratory Carbon Fiber pathway report, accessed from the National Renewable Energy Laboratory database. The inputs and outputs associated with the production of 1 kg of AN are shown below in Table 1. The AN provider's exact energy and electricity usage is unknown, so energy and electricity inputs were borrowed from the reference data. Additionally, impacts associated with the production and transport of equipment were excluded from the study.

Inputs	**Amount**	**Unit**
Ammonia	0.456	kg
Coal, combusted	0.019	kg
Electricity, AC, 120V	0.3996	MJ
Natural gas	0.038	m3
Propylene	1.116	kg
Residual fuel oil, combusted	0.001	l
Outputs	**Amount**	**Unit**
Acrylonitrile	1	kg

Table 1- AN production inventory analysis

2.2 Polyacrylonitrile Production

Polyacrylonitrile (PAN) is produced through the polymerization of AN. PAN production can occur on-site at the carbon fiber manufacturing facility or a separate facility. For this LCA, it was assumed that PAN was produced on-site. PAN production data was obtained from the 2019 Argonne National Laboratory Carbon Fiber pathway report, accessed from the National Renewable Energy Laboratory database. The inputs and outputs of this process can be seen below. The exact energy and electricity usage is unknown, so energy and electricity inputs were borrowed from the reference data. Additionally, impacts associated with the production and transport of equipment were excluded from the study.

Inputs	Amount	Unit
Acrylonitrile	0.96	kg
Coal, combusted	0.344	kg
Electricity, AC, 120V	5.22	MJ
Methyl methacrylate	0.05	kg
Natural gas	0.944	m3
Residual fuel oil	0.333	l
Output	**Amount**	**Unit**
Polyacrylonitrile	1	kg

Table 2- PAN production inventory analysis

2.3 Carbon Fiber Manufacturing

Carbon fiber manufacturing involves several key steps: PAN spinning, oxidation, stabilization, carbonization, surface treatment, washing, sizing, drying, and winding. Energy and electricity requirements were modeled based on the 2019 Argonne National Laboratory Carbon Fiber pathway report, accessed from the National Renewable Energy Laboratory database. The electricity consumption mix was adapted based on the manufacturer's location and power supplier.

Several emissions result from carbon fiber processing due to material loss during the chemical conversion from PAN to carbon fiber. These emissions are detailed in Figure 3 and were sourced from a 2023 LCA for carbon fiber manufacturing [1].

Input	Amount	Unit
Polyacrylonitrile	2.08	kg
Natural gas, combusted	1.97E-1	m3
Electricity, AC, 120V	76.75	MJ
Output	**Amount**	**Unit**
Carbon fiber	1	kg
Sulfuric acid	11.99E-2	kg
Ethane	1.01E-5	kg

Ammonia	1.16E-3	kg
Hydrogen cyanide	1.57E-2	kg
Carbon monoxide	3.24E-3	kg
Carbon dioxide	1.01	kg
Wastewater	5.5	kg

Table 3- Carbon fiber manufacturing inventory analysis

2.4 Waste fiber processing

Omnia Products, LLC obtains waste fiber material from carbon fiber manufacturers. The fiber is re-spooled and then chopped according to customer requirements. The company's electricity and gas consumption were obtained from Duke Energy Progress and Dominion Energy. 35% of electricity and gas were allocated to the process of this study based on assumptions provided by Omnia Products. The average monthly consumption was 6359 kWh of electricity and 0.15 m^3 of natural gas. Omnia Products processes 1 MT of chopped waste carbon fiber daily and a 10-hour work day was assumed. These assumptions determined the power requirements to produce 1 kg of waste carbon fiber.

The key consumable used in this process is steel blades. Each blade weighs 0.027 kg and 72 blades are used in a setup to chop the waste fiber. This full setup produces anywhere from 1,000-2,000 kg before needing to be replaced. Based on these inputs provided by Omnia Products, the amount of steel blades used to produce 1 kg of fiber was calculated. Impacts associated with the production and transport of equipment were excluded from the study.

Inputs	**Amount**	**Unit**
Electricity, AC, 120 V (Duke Energy Carolinas)	0.082	kWh
Natural gas	0.05	m3
Steel blades	1.31E-3	kg
Outputs	**Amount**	**Unit**
Chopped fiber	1	kg

Table 4- Waste fiber processing inventory analysis

2.5 Transportation steps

Transportation distances were calculated using city locations, shown below in Table 5. Long-haul, diesel-powered combination trucks were used to model ground transportation steps. Air transportation distances rely on the assumption that the materials are transported directly between the airports nearest the manufacturer and Omnia Products. Initial ground transport from airports was not included in the scope of the process. The source of AN for the carbon fiber manufacturer is not known, however, China is the majority manufacturer of AN [2], so it was assumed the manufacturer sourced from China and used ocean freight to obtain the material.

Step	Initial location	Final location	Distance (km)	Transportation method
Virgin material to end user	Southeastern United States	Midwestern United States	1179.65	Ground
Waste material to Omnia	Southeastern United States	Midatlantic United States	923.76	Ground
Omnia to end user	Midatlantic, United States	Midwestern United States	1256.63	Ground
Consumables to Omnia	Germany	Midwestern United States	6713	Air
AN to PA/CF manufacturer	China	Southeastern United States	13484	Ocean

Table 5- Transportation inventory analysis

2.6 Inventory exclusion considerations

Production equipment was excluded from the inventory analysis due to their long operational lifespans, often spanning decades. The environmental impacts associated with the production and disposal of the equipment would be distributed over the entire lifespan, so the impact of the equipment on a single functional unit is negligible. Gaseous and wastewater emissions associated with AN and PAN production were excluded given the limited availability of information within the National Renewable Energy Laboratory (NREL) database from the LCA Commons. Disposal of Omnia Products' consumables were not included in the system boundary given the low impact relative to the company's operations (see section 3.4).

3. Life Cycle Impact Assessment

3.1 Impact categories and assessment methods

Data for this study was sourced from the National Renewable Energy Laboratory (NREL) database from the LCA Commons. The impact assessment utilized the EPA's TRACI 2.1 (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) methodology. TRACI 2.1 was chosen based on its alignment with U.S. regulatory and environmental priorities and widespread acceptance in LCA studies. The LCA modeling software used was openLCA.

Emissions are the major impact under consideration for this study based on the preferences and priorities of Omnia Products and its customers. Global warming potential (GWP) is the metric used to quantify emissions and is defined as the ability of gases (CO_2, methane, nitrous oxides) to trap heat. All gases are normalized and aggregated into a common unit, CO_2 equivalents (CO_2eq). Other impact methods were calculated and are included within Appendix 6.1 of the report.

3.2 Comparative emissions results

Purchasing 1 kg of virgin carbon fiber causes 29.30 kg CO_2 eq emitted. while only 6.15 kg CO_2eq is associated with purchasing 1 kg of waste carbon fiber. Utilizing waste material over virgin carbon fiber results in a 79.01% reduction in emissions.

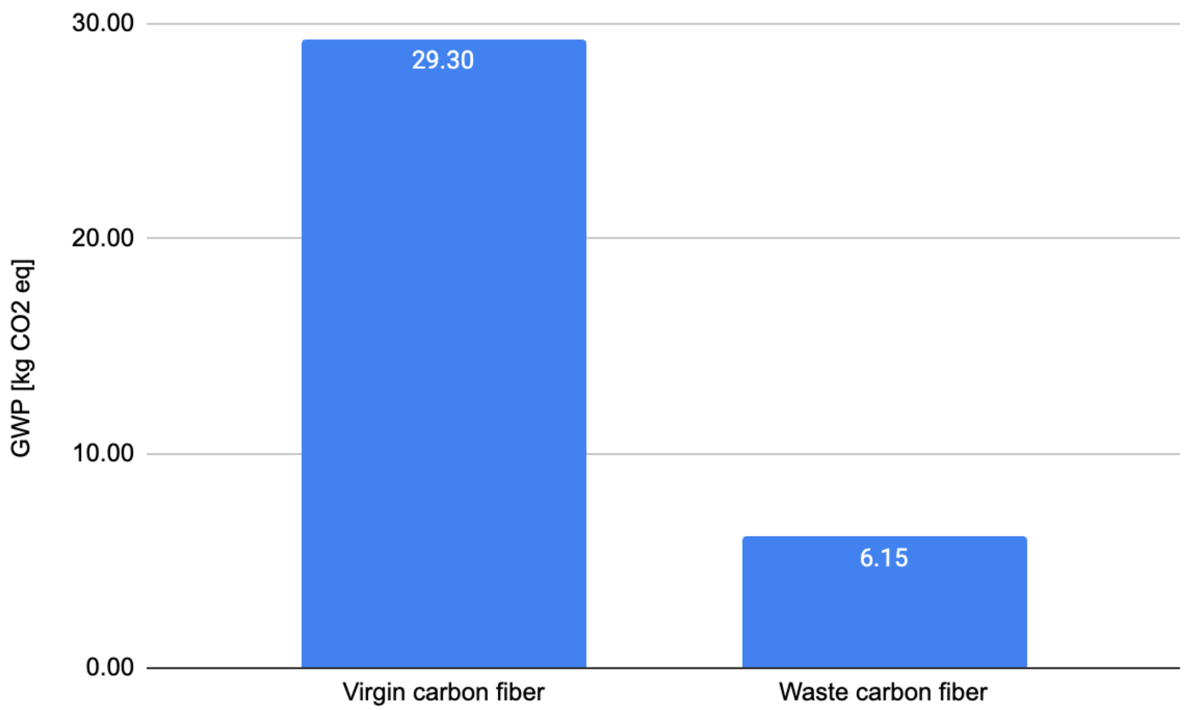

Figure 3- Emissions of each product system

Additional impact results from each system, not included in the focus of the study, are shown in Appendix 6.1.

3.3 Virgin carbon fiber system

Figure 4 shows the breakdown of emissions by source. Electricity and energy are responsible for most of the emissions (12.83 and 10.48 kg CO_2eq, respectively) of producing 1 kg of virgin carbon fiber. Raw materials account for about 5.75 kg CO_2eq (~20%). Transportation accounts for less than 1% (0.12 kg CO_2eq) of the emissions of this system.

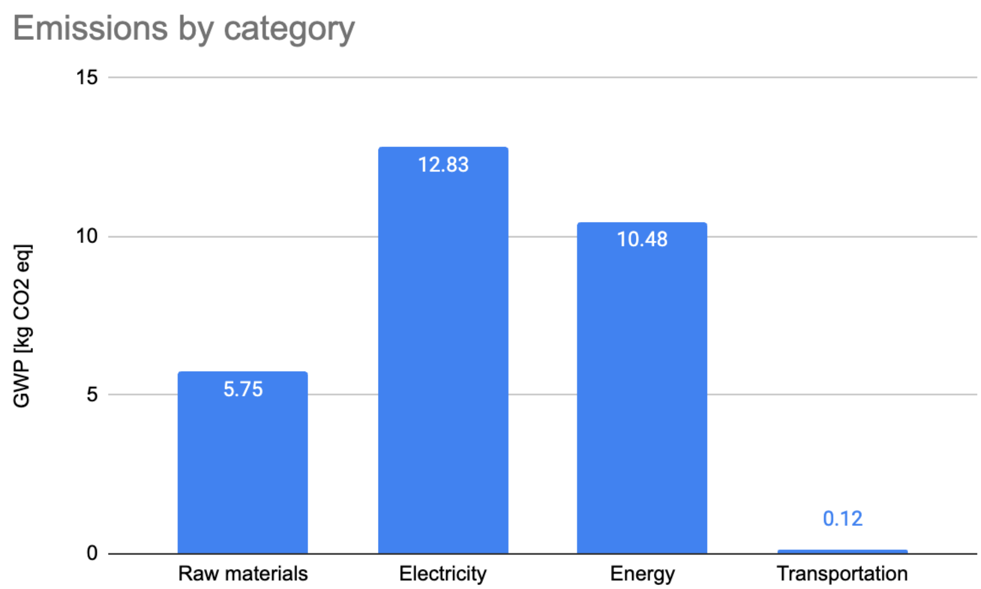

Figure 4- Emissions by category for virgin fiber product system

A more detailed flow and emissions accounting for this system is shown below in Figure 5. Emissions largely fall into raw material production and electricity and energy categories. Much of the emissions associated with raw material production can also be traced to electricity and energy requirements.

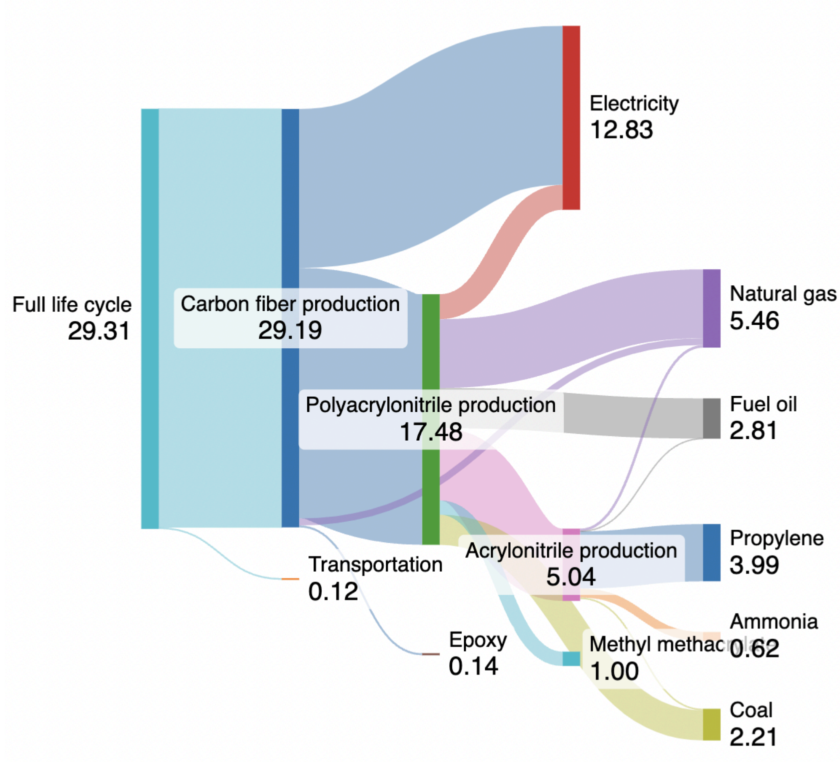

Figure 5- Sankey diagram detailing the flow of emissions for virgin fiber product system

3.4 Waste fiber system

A vast majority of the emissions (~96%) come from transportation. 2.4% of the emissions (0.15 kg CO_2 eq] come from energy and electricity, while raw materials account for less than 1% of emissions (0.003 kg CO_2 eq).

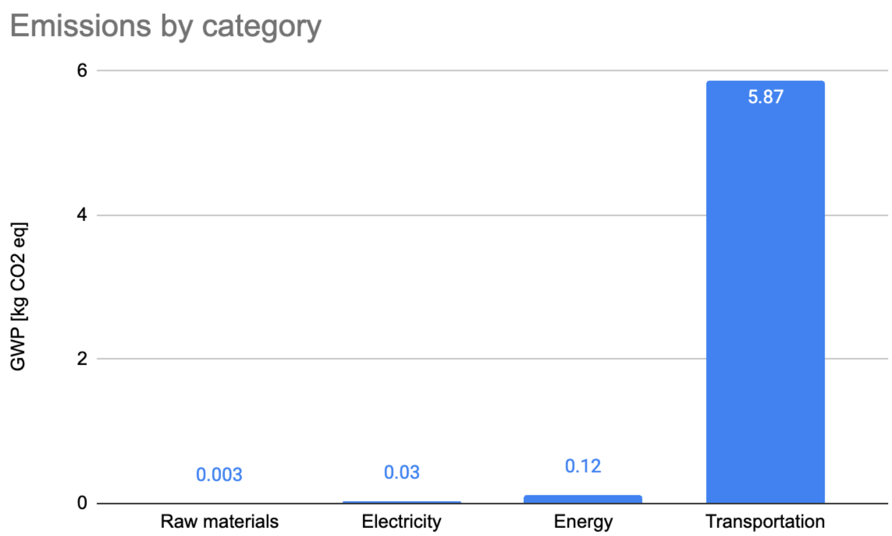

Figure 6- Emissions by category for waste fiber product system

A more detailed flow and emissions accounting for this system is shown below in Figure 7. The bulk of emissions result from transportation of the steel blades via air freight. A small portion of emissions are due to the waste fiber processing.

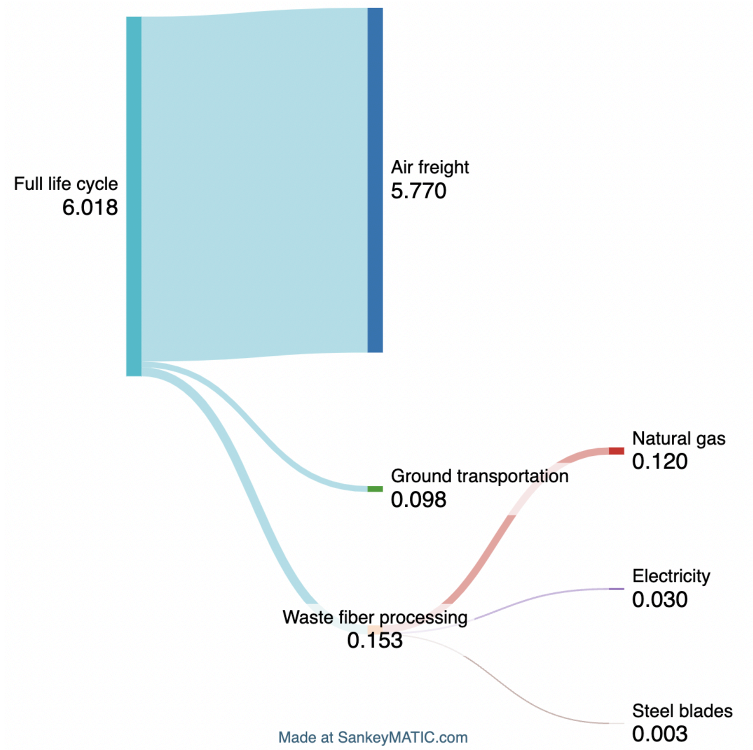

Figure 7- Sankey diagram detailing the flow of emissions for waste fiber product system

4. Interpretation and considerations

4.1 Comparison of systems

Purchasing waste fiber over virgin fiber would decrease the end customer's emissions by 79.01%. This large difference is due to the classification of waste carbon fiber as a secondary, post-industrial waste (as defined by ISO 14044:2006 Clause 4.3.4.2), so all impacts are allocated to the primary product, the virgin carbon fiber.

4.2 Considerations

4.2.1 Virgin carbon fiber system

AN, PAN, and carbon fiber manufacturing produce emissions to water, air, and terrestrial sources due to loss of material upon processing. These emissions were only considered for carbon fiber manufacturing since robust data was available for this process. Emissions for AN and PAN processing were not considered given the lack of information available. Inclusion of these emissions would increase the overall emissions within this system.

4.2.2 Waste carbon fiber system

Disposal of consumables were excluded from the study since there was almost negligible material used per functional unit of the end product. The material is also highly recyclable, which would lower the emissions of the system. Landfilling the material can potentially leach toxic materials into terrestrial and water systems. The fate of the product is unknown, therefore allocation to these end-of-life options would be hard to determine.

4.2.3 Cut-off approach

The cut-off approach was used based on ISO 14044 guidelines, which classify the waste fiber as a secondary material. These guidelines allocate all impacts downstream to the primary product. While this method is acceptable and widely used in LCA modeling, it may be more accurate to allocate processes downstream of carbon fiber manufacturing to this system (resources used to produce AN and PAN production).

5. Sources

[1] Prenzel, Tobias Manuel, et al. “Bringing light into the dark—overview of environmental impacts of carbon fiber production and potential levers for reduction.” *Polymers*, vol. 16, no. 1, 19 Dec. 2023, p. 12, https://doi.org/10.3390/polym16010012.

[2] “Acrylonitrile Market Size and Share: Industry Report, 2030.” *Acrylonitrile Market Size And Share | Industry Report, 2030*, www.grandviewresearch.com/industry-analysis/acrylonitrile-acn-market#:~:text=Acrylonitrile%20is%20classified%20as%20a,open%20new%20avenues%20for%20growth. Accessed 22 Dec. 2024.

6. Appendix

6.1 Additional impact categories

Impact category	Units	Virgin material	Waste material	Percent reduction for waste material
Acidification	kg SO2 eq	7.33E-02	1.59E-02	78.31%
Eutrophication	Kg N eq	5.43E-03	25.6E-03	-3.13%
Freshwater ecotoxicity	CTUeco	1.02E+03	1.22E+01	98.80%
Global warming	Kg CO2 eq	2.93E+01	6.15	79.01%
Human health-cancer	CTUcancer	2.14E-06	2.57E-08	98.80%
Human health-non-cancer	CTUnoncancer	3.98E-04	4.77E-06	98.80%
Human health-particulate matter	PM 2.5 eq	5.11E-03	4.03E-04	92.11%
Ozone depletion	kg CFC -11 eq	2.51E-07	2.49E-08	90.08%
Smog formation	kg O3 eq	9.35	5.12E-01	94.52%