

# **Life Cycle Assessment of a Wind Turbine Blade: A Comparative Perspective of Materials and Disposal Methods**

Term Project Report Submitted in partial fulfilment of the requirements of the Course  
**CC5610: Concepts of Sustainability**

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# **Abstract**

This Life Cycle Assessment (LCA) report comprehensively evaluates the environmental impact of wind turbine blades by comparing two primary materials: Glass Fiber Reinforced Polymer (GFRP) and Carbon Fiber Reinforced Polymer (CFRP). The study meticulously examines the manufacturing phase, focusing on carbon emissions associated with material production. Additionally, it delves into end-of-life disposal methods, considering landfilling, incineration, and mechanical recycling, to assess their respective carbon footprints. Our findings reveal that while GFRP is cost-effective, its disposal methods pose significant environmental challenges especially in the face of increasing wind farm installations. On the other hand, CFRP, despite its higher production energy, presents a more sustainable solution when considering its reduced weight and potential for recycling. The study explores various material combinations, emphasizing the significance of optimizing material proportions to minimize carbon emissions while ensuring performance. This report underscores the complexity of material choices, emphasizing the crucial balance between economic viability, structural performance, and environmental impact. By presenting a detailed analysis of these factors, this study offers valuable insights for decision-makers in the wind energy industry, facilitating informed choices aligned with project objectives and environmental stewardship.

**Keywords:** Wind Turbine Blade, LCA, GFRP, CFRP, EoL, Mechanical Recycling

## **Abbreviations**

GWP, Global warming potential; ISO, International Organization for Standardization; LCA, Life cycle assessment; LCI, Life cycle inventory; LCIA, Life cycle impact assessment; EoL, End of life; VARTM, Vacuum Assisted Resin Transfer Moulding method, WTB, Wind Turbine Blade.



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# Chapter 1      Introduction

We recognize the pivotal role that wind energy plays in addressing the global need for renewable energy sources. Wind turbines (WT) have become emblematic of our commitment to reducing greenhouse gas emissions, fostering sustainability, and curbing climate change. However, it is also essential to acknowledge that the environmental impact of wind energy installations extends beyond their operational phase and includes considerations such as material selection and end-of-life disposal.

Wind energy stands as a beacon of hope in our pursuit of a sustainable energy future. It offers the promise of clean and renewable electricity generation, thus mitigating the detrimental effects of fossil fuel dependency on our environment. Wind turbines, with their towering presence on landscapes, have become icons of progress, symbolizing our collective efforts to reduce our carbon footprint. Nevertheless, we cannot overlook the environmental implications associated with their manufacturing, operation, and disposal.

One of the most critical decisions in the life cycle of a wind turbine blade is the selection of materials for its construction. This decision inherently impacts the carbon emissions associated with its production. In this report, we delve into a meticulous analysis of the two primary material choices: Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP). By comparing the CO<sub>2</sub> emissions during their manufacturing processes, we aim to provide a thorough understanding of the environmental footprint linked to material selection. Our findings will serve as a vital guide for making informed choices that optimize sustainability in the early phases of wind turbine production.

However, our investigation does not stop at the manufacturing stage. We extend our analysis to the critical end-of-life disposal phase, recognizing that wind turbine blades have a finite operational lifespan. The way these blades are decommissioned and disposed of can significantly impact their environmental legacy. This report meticulously evaluates various disposal methods, considering their carbon emissions, resource utilization, and long-term environmental consequences, with specific focus on scenarios involving both CFRP and GFRP materials.

Ultimately, our report seeks to offer a holistic assessment of the entire life cycle of wind turbine blades, including material selection and end-of-life considerations. By weighing the

carbon emissions throughout the lifecycle, we aspire to provide the broader wind energy industry with valuable insights into sustainable choices. Our goal is to support decision-makers in adopting environmentally responsible practices that align with the company's commitment to renewable energy and environmental stewardship.

## Chapter 2 Literature Review, Objectives

### 2.1 Literature Review

*Table 1: Existing works of literature on LCA of wind turbines, turbine blades, turbine blade materials etc.*

Sl No.	Focus of study	Considerations	Observations	Software or data base	Reference
1.	Wind turbine blade wastes and the environmental impacts in Canada	Estimation of the cumulative waste inventory in Canada until 2050. Five waste management options landfills, incineration with municipal waste, incineration in cement kilns, mechanical recycling with landfilling and mechanical recycling with incineration.	Of total waste, approximately 25% is related to the manufacture of wind turbine blades. Incineration is a significant source of GHG emissions. Mechanical recycling can achieve substantial reductions in PED and GHG emissions but achieving financial viability would require substantial regulatory support. The higher financial value of Carbon Fibers used justify recycling as a waste management route.		[1]
2.	To assess the environmental viability of several waste management options for CFRP waste.	Comparative LCA analysis of waste treatment options for CFRP materials. Primary energy consumption, global warming potential in 100 years	Full life cycle assessment of different waste management options for CFRP waste and provides the first comparison of CFRP recycling technologies based on existing, standardized, or experimental data.	Open lca	[2]

3.	Macr oscopic quantitative assessment of the lifetime environment al impact of WT blades.	Energy consumption, co <sub>2</sub> emissions and water consumption during manufacturing, transportation, operation, and maintenance stages End of life recycling of material was not considered in this study.	Same rated power blades can have environmental impacts differing by up to 46% due to difference in size and operating conditions. Manufacturing accounts for more than 96% of the whole blade life cycle energy consumption	Eco data	[5]
4.	Liter ature overview exploring the materials for Wind Turbine Blades	Traditional composite materials like Glass fibers and Epoxy matrix composite. Modern Carbon fibers, Hybrid and Nanoengineered composites.	The high performance of large to extra-large wind turbines can only be fulfilled by using advanced, lightweight, exceptionally durable, fatigue resistant and damage tolerant and stiff composite material. Carbon fibers represent a promising alternative.		[6]
5.	Brief review on recycling and reuse of wind turbine blade materials	Waste Glass Fiber or Carbon Fiber composites' recycling through mechanical, thermal (pyrolysis and oxidation in fluidized bed) and chemical processes.	Carbon fiber has the highest recycling energy consumption of 183- 286 MJ/kg. Recycling energy consumption for mechanical processes is minimum the same for chemical processes are highest. Due to reduced mechanical qualities of Recycled Glass Fibers and inexpensiveness of Virgin Glass Fibers there is an apathy towards recycling of turbine blades which could cause great ecological impact after the end of life.		[7]

## 2.2 Objective

Life Cycle Assessment of a wind turbine blade is conducted following ISO 14040 standard, [and its Sustainability evaluation and assessment is performed.](#)

### 2.2.1 Goal and Scope

The goal of this study is to (i) identify the environmental impact of a 67-meter Wind Turbine blade throughout its life cycle and (ii) Compare GFRP and CFRP as most representative material of WTB based on environmental impact associated during manufacturing stage. (iii) Comparative assessment of three end of life disposal methods and consequent viability study of the material and EOL process based on total CO<sub>2</sub> emitted during whole lifecycle. [\(iv\) Comparative Sustainability evaluation of GFRP and CFRP as WTB material based on UN SDGs and Targets.](#)

### 2.2.2 System

The system focused on for this study consists of the manufacturing stage and end of life treatment of the blade. The manufacturing stage consists of selecting the suitable materials and preparing them according to the required shape and sizes and then moulding the blade followed by the finishing processes. End of life is considered after 100 percent of the blade is decommissioned.

### 2.2.3 Functional Unit

One unit of 67-meter Wind Turbine Blade.

### 2.2.4 Assumptions

1. Cradle-to-grave study is considered.
2. Transportation, Operation and Maintenance phase is excluded from study.

3. Vacuum Assisted Resin Transfer Moulding (VARTM) method is used to fabricate the composite wind turbine blade.
4. Energy consumption during the manufacturing processes is not considered for consequent CO<sub>2</sub> calculations.
5. For comparative study one composite material is assumed by completely substituting glass fibre by Carbon fibre (GFRP: CFRP=0:100 by volume) for hypothetical case, and other composite material is assumed to have 50:50 proportion of GFRP and CFRP.
6. While recycling carbon fibre the whole percentage of recovered CF is assumed to substitute the virgin carbon fibre.

## **Chapter 3      Methodology**

### **3.1 GFRP composite**

In our first method, we focused on assessing the environmental impact of a 67-meter wind turbine blade constructed primarily from glass fiber reinforced polymer (GFRP) as a composite material. We obtained data on the mass of each component and their respective carbon dioxide (CO<sub>2</sub>) footprints throughout the lifecycle from raw material extraction to manufacturing. The CO<sub>2</sub> footprint data for glass fiber was sourced from the TRACI 2.1 database within the Eco Invent database in the Open LCA software.

After manufacturing the blade, we deliberately excluded the CO<sub>2</sub> footprints associated with transportation and operational phases, as they fell outside the scope of our study. Now, let's delve into the disposal phase of GFRP. We explored two disposal pathways as shown in Figure 1. First, we considered landfilling with municipal solid waste. However, the CO<sub>2</sub> footprint associated with landfilling was found to be negligible and therefore was not calculated separately. In the second disposal pathway, we explored incineration as an alternative. The rationale behind this pathway was to reduce the overall land use associated with landfilling. Since glass fiber is incombustible and has a negligible calorific value, we.

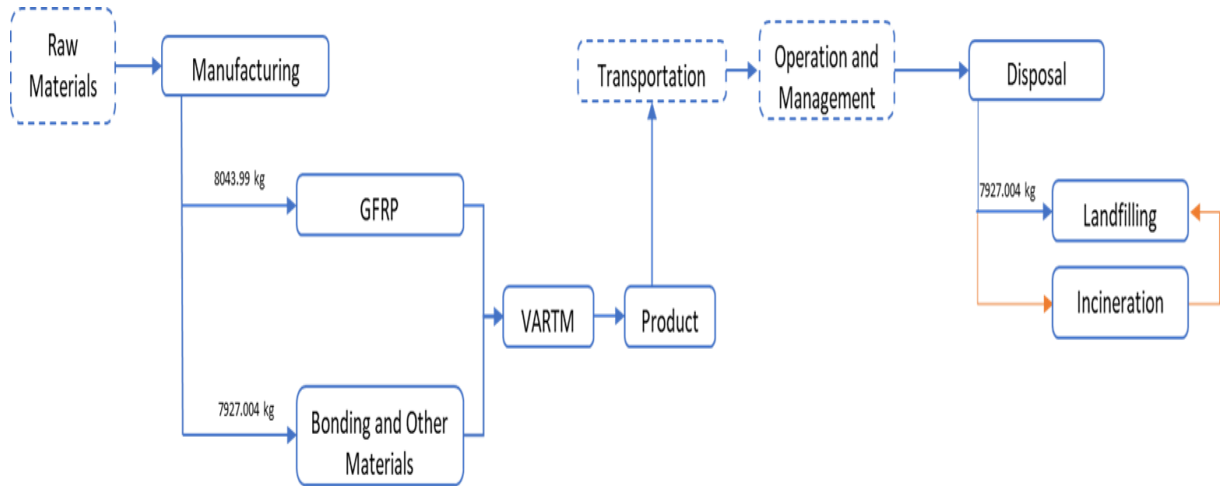


Figure 1: Supply chain for GFRP based blade.

focused our incineration calculations solely on the matrix and bonding materials. Data for the incineration CO<sub>2</sub> footprint was derived from literature.[1]

Table 1: Total GWP calculation for GFRP based blade.

Material	Amount	CFRP (CO <sub>2</sub> eq kg/kg)	Total GWP (kg CO <sub>2</sub> eq)
Glass Fiber	8043.99	8.46	68052.1554
Mate	42.924	3.51	150.66324
Resin	3970.48	5.8	23028.784
Glue	643.86	6.59	4243.0374
Inserts	157.75	3.02	476.405
Receivers	59.02	3.6	212.472
Gel Coat	131.99	4.93	650.7107
Pastes	34.34	4.93	169.2962
Topcoat	49.36	4.79	236.4344
Balsa	805.9	0.601	484.3459
PVC/PET	80.48	2.47	198.7856
Taky tape	94.43	4.45	420.2135
Glitter tape	471.09	5.75	2708.7675
Vacuum bag	106.24	4.68	497.2032
Mesh	1269.48	3.1	3935.388
Peel Ply	9.66	1.14	11.0124
Total	15970.994		105475.6744
CO <sub>2</sub> production due to incineration (kg)=			4756.2024
Total			110231.8768



The remaining ash resulting from incineration, when mixed with the glass fiber waste, was disposed of in a landfill. In the end, we calculated the total carbon footprint for both disposal pathways to provide a comprehensive understanding of the environmental impact of disposing of GFRP materials.

Carbon Footprint of the blade with GFRP as main material and landfiling as disposal method =  $\sum (\text{Material in kg} \times \text{CO}_2 \text{ eq kg/kg})$

Carbon Footprint of the blade with GFRP as main material and incineration as disposal method =  $\sum (\text{Material in kg} \times \text{CO}_2 \text{ eq kg/kg}) + (\text{kg waste from bonding and other materials} \times 0.6 \text{ CO}_2 \text{ eq kg/kg blade waste})$

### 3.2 CFRP composite

In our second method, we explored the environmental impact of substituting glass fibre with carbon fibre entirely, based on volume proportions. This substitution, while not commercially practiced, serves as a hypothetical scenario for evaluating environmental implications. The weight reduction values corresponding to different volume proportions of Glass Fiber Reinforced Polymer (GFRP) and Carbon Fiber Reinforced Polymer (CFRP) were obtained from literature.[2]

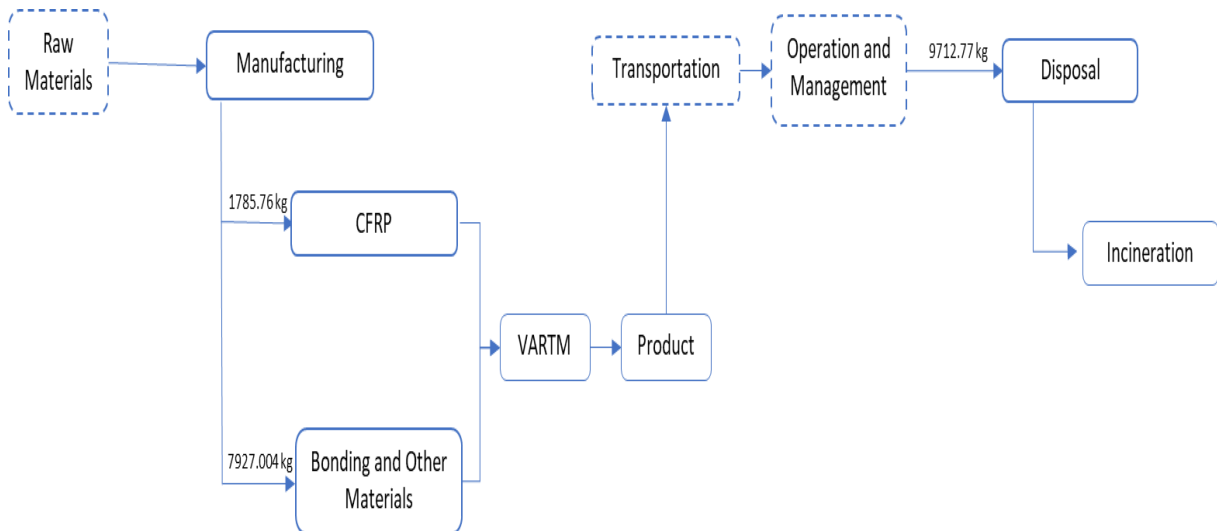


Figure 2: Supply chain for CFRP based blade with incineration as disposal method.

The manufacturing phase CO<sub>2</sub> footprint of CFRP is taken from literature.[3] And remaining material CO<sub>2</sub> footprint is like the first case. In the disposal phase, we explored two distinct pathways. Given that CFRP is not typically disposed of in sanitary landfills due to high material cost and environmental concerns after degradation further wards, we omitted this disposal by landfill method.

*Table 2: Total GWP calculation for CFRP based blade with incineration as disposal.*

Material	Amount	CFP (CO <sub>2</sub> eq kg/kg)	Total GWP kg
Carbon Fibre (0/100 vol ratio)	1785.76578	18.4	32858.09035
Mate	42.924	3.51	150.66324
Resin	3970.48	5.8	23028.784
Glue	643.86	6.59	4243.0374
Inserts	157.75	3.02	476.405
Receivers	59.02	3.6	212.472
Gel Coat	131.99	4.93	650.7107
Pastes	34.34	4.93	169.2962
Topcoat	49.36	4.79	236.4344
Balsa	805.9	0.601	484.3459
PVC/PET	80.48	2.47	198.7856
Taky tape	94.43	4.45	420.2135
Glitter tape	471.09	5.75	2708.7675
Vacuum bag	106.24	4.68	497.2032
Mesh	1269.48	3.1	3935.388
Peel Ply	9.66	1.14	11.0124
Total	9712.76978		70281.60939
CO <sub>2</sub> production due to incineration			10327.79163
Total			80609.40103

The first pathway involved direct incineration shown in the supply chain Figure 2. Data on amount of CO<sub>2</sub> emission per kg of blade CFRP waste incineration was sourced from a reference paper.[3] In the second disposal pathway, we considered recycling carbon fibre in conjunction with incineration. We acquired data on material recovery percentage and the

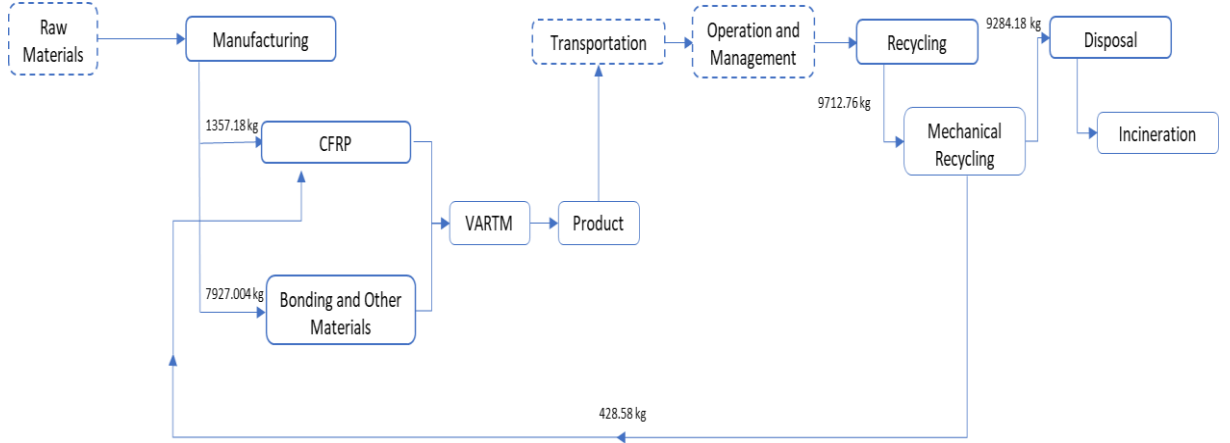


Figure 3: Supply chain for CFRP based blade with Mechanical Recycling then incineration as disposal method.

amount of incinerated material from a reference paper.[4] We have considered that the CFRP material recovered from the recycling process is completely used in the material input and consequent reduction of virgin carbon fibre is considered in the calculation during mass balance of the supply chain shown in Figure 3.

We then calculated the total CO<sub>2</sub> footprint for both disposal pathways, enabling a comprehensive analysis of the environmental consequences associated with the use and disposal of CFRP, particularly when considering different end-of-life scenarios.

Carbon Footprint of the blade with CFRP as main material and incineration as disposal method =  $\sum (\text{Material in kg} \times \text{CO}_2 \text{ eq kg/kg}) + (\text{kg waste from bonding and other materials} \times 0.6 \text{ kg CO}_2 \text{ eq kg/kg blade waste}) + (\text{kg waste CFRP} \times 3.12 \text{ CO}_2 \text{ eq kg/kg blade waste})$ .

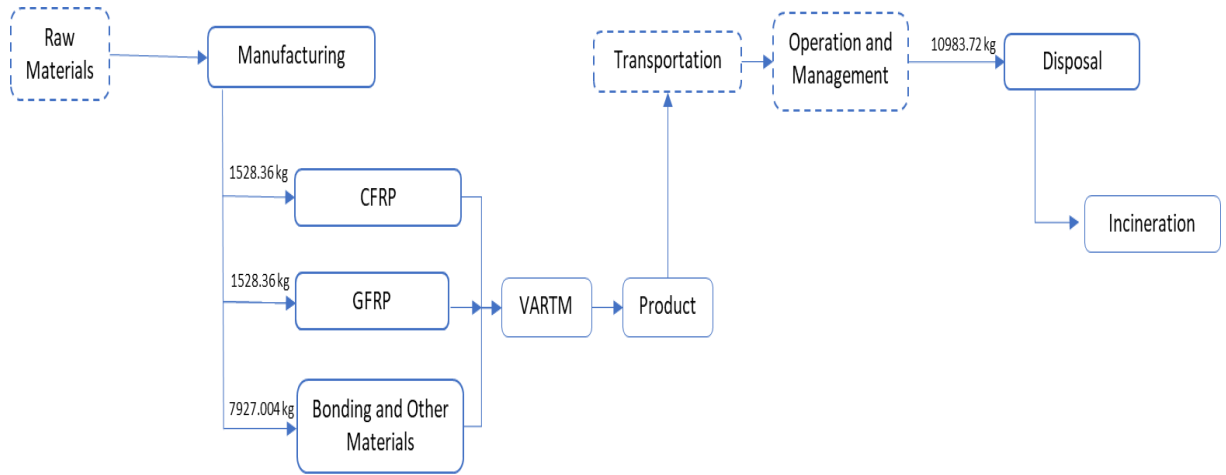
Carbon Footprint of the blade with CFRP as main material and Mechanical Recycling followed by incineration as disposal method =  $\sum (\text{Material in kg} \times \text{CO}_2 \text{ eq kg/kg}) + (\text{kg waste from bonding and other materials} \times 0.6 \text{ kg CO}_2 \text{ eq kg/kg blade waste}) + (\text{kg recycled CFRP} \times 0.035 \text{ CO}_2 \text{ eq kg/kg recycled material}) + (\text{kg waste CFRP} \times 3.12 \text{ CO}_2 \text{ eq kg/kg blade was recycled})$

*Table 3: Total GWP calculation for CFRP based blade with Mechanical Recycling.*

Material	Amount	CFP (CO <sub>2</sub> eq kg/kg)	Total GWP kg
Carbon Fibre	1357.1819	18.4	24972.14867
Mate	42.924	3.51	150.66324
Resin	3970.48	5.8	23028.784
Glue	643.86	6.59	4243.0374
Inserts	157.75	3.02	476.405
Receivers	59.02	3.6	212.472
Gel Coat	131.99	4.93	650.7107
Pastes	34.34	4.93	169.2962
Topcoat	49.36	4.79	236.4344
Balsa	805.9	0.601	484.3459
PVC/PET	80.48	2.47	198.7856
Taky tape	94.43	4.45	420.2135
Glitter tape	471.09	5.75	2708.7675
Vacuum bag	106.24	4.68	497.2032
Mesh	1269.48	3.1	3935.388
Peel Ply	9.66	1.14	11.0124
Total	9284.1859		62395.66771
CO <sub>2</sub> production due to incineration			8990.610218
CO <sub>2</sub> due to mechanical recycling			15.00043255
Total			71401.27836

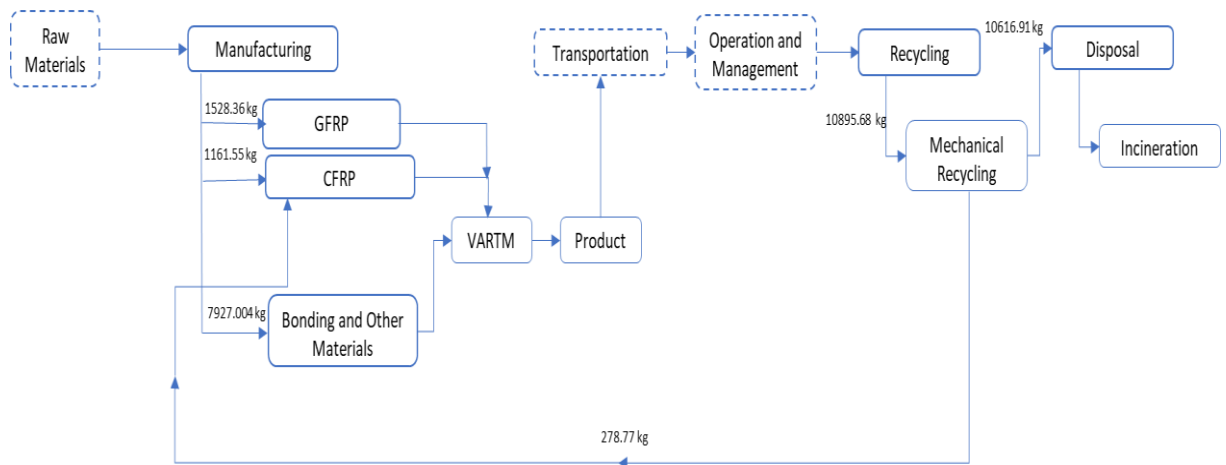
### 3.3 GFRP and CFRP composite

In our third material scenario, we've considered a composite material that closely aligns with commercial practices. In this case, we've substituted 50 percent of the glass fiber with carbon fiber. The weight reduction corresponding to this proportion was determined based on data obtained from literature.[2] Methodology for calculating the carbon dioxide (CO<sub>2</sub>) footprint during the manufacturing stage and the disposal stage for this third material is consistent with our second material scenario. We've maintained the same two disposal



*Figure 4: Supply chain for CFRP + GFRP based blade with incineration as disposal method.*

pathways for this assessment. i.e. 1<sup>st</sup>-disposal by incineration and 2<sup>nd</sup>-disposal by recycling with incineration. In both methods the residual ash and glass fiber is further disposed of to the nearest landfill.



*Figure 5: Supply chain for CFRP + GFRP based blade with Mechanical Recycling then incineration as disposal method.*

Carbon Footprint of the blade with 50/50 CFRP and GFRP and incineration as disposal method =  $\sum (\text{Materials in kg} \times \text{CO}_2 \text{ eq kg/kg}) + (\text{kg waste from bonding and other materials} \times 0.6 \text{ kg CO}_2 \text{ eq/kg blade waste}) + (\text{kg waste CFRP} \times 3.12 \text{ CO}_2 \text{ eq kg/kg blade waste})$ .

Table 4: Total GWP calculation for CFRP + GFRP based blade with incineration.

Material	Amount	CFP (CO <sub>2</sub> eq kg/kg)	Total GWP kg
Glass fibre	1528.3581	8.46	12929.90953
Carbon Fibre	1528.3581	18.4	28121.78904
Mate	42.924	3.51	150.66324
Resin	3970.48	5.8	23028.784
Glue	643.86	6.59	4243.0374
Inserts	157.75	3.02	476.405
Receivers	59.02	3.6	212.472
Gel Coat	131.99	4.93	650.7107
Pastes	34.34	4.93	169.2962
Topcoat	49.36	4.79	236.4344
Balsa	805.9	0.601	484.3459
PVC/PET	80.48	2.47	198.7856
Taky tape	94.43	4.45	420.2135
Glitter tape	471.09	5.75	2708.7675
Vacuum bag	106.24	4.68	497.2032
Mesh	1269.48	3.1	3935.388
Peel Ply	9.66	1.14	11.0124
Total	10983.72		78475.21761
CO <sub>2</sub> production incineration			9524.679672
Total			87999.89728

Carbon Footprint of the blade with 50/50 CFRP and GFRP and Mechanical Recycling followed by incineration as disposal method =  $\sum (\text{Material in kg} \times \text{CO}_2 \text{ eq kg/kg}) + (\text{kg waste from bonding and other materials} \times 0.6 \text{ kg CO}_2 \text{ eq kg/kg blade waste}) + (\text{kg recycled CFRP} \times 0.035 \text{ CO}_2 \text{ eq kg/kg recycled material}) + (\text{kg waste CFRP} \times 3.12 \text{ CO}_2 \text{ eq kg/kg blade waste})$

*Table 5: Total GWP calculation for CFRP + GFRP based blade with Mechanical Recycling.*

Material	Amount (kg)	CFP (CO <sub>2</sub> eq kg/kg)	Total GWP (kg)
Glass fibre	1528.3581	8.46	12929.9095
Carbon Fibre	1161.5521	18.4	21372.5596
Mate	42.924	3.51	150.66324
Resin	3970.48	5.8	23028.784
Glue	643.86	6.59	4243.0374
Inserts	157.75	3.02	476.405
Receivers	59.02	3.6	212.472
Gel Coat	131.99	4.93	650.7107
Pastes	34.34	4.93	169.2962
Topcoat	49.36	4.79	236.4344
Balsa	805.9	0.601	484.3459
PVC/PET	80.48	2.47	198.7856
Taky tape	94.43	4.45	420.2135
Glitter tape	471.09	5.75	2708.7675
Vacuum bag	106.24	4.68	497.2032
Mesh	1269.48	3.1	3935.388
Peel Ply	9.66	1.14	11.0124
Total	10616.914		71725.9882
CO <sub>2</sub> production incineration			8380.24512
CO <sub>2</sub> due to mechanical recycling			9.75703811
Total			80115.9904

### 3.4 Methodology for Sustainability Assessment

We categorized the impacts of our project in connection with UN Sustainable Development Goals as Direct, Indirect, None and numbered them as 2, 1, 0 respectively for Positive Impacts whereas corresponding negative values were given for representing Negative Impacts. Each of the 169 Targets were analysed and numbered accordingly.

Total Positive and Negative impact values are counted separately for both composite materials in order to evaluate a Sustainability Score of each type. Further individual scores are also calculated for each of the 17 SDGs. This score is divided by- [No of Targets in that SDG  $\times$  2], here, 2 is the maximum possible score for one target as mentioned above. This normalised score is converted to a scale of 100. Now the SDGs are arranged in descending order of normalised scores.

## Chapter 4 Sustainability

The 17 UN SDGs provide a framework to represent and evaluate sustainability. Here a method has been explored to quantify the connections of impacts with the SDGs based on the Targets to get an overall Sustainability Score which can be used to compare sustainability between different processes or materials. Further through ordering the SDGs according to individual scores for a particular process or material, a sense can be achieved about the quality of impacts it leaves on a particular sector represented by each SDG.

Connection of each goal to this project is explored through each Target as follows:

In SDG 1-

Target 1.1 aims to reduce poverty by at least half by 2030, focusing on all dimensions of poverty. Our LCA project indirectly aligns with this goal by making clean energy more accessible to communities. Access to affordable energy is crucial for poverty reduction as it enables economic activities, improves living conditions, and creates opportunities for income generation.

Target 1.2 aims to reduce at least by half the proportion of men, women, and children of all ages living in poverty in all its dimensions according to national definitions. Target 1.4



*Table 6: Target wise sustainability scores for SDG 1.*

SDG	Targets	GFRP	CFRP	Normalised GFRP	Normalised CFRP
1. End poverty in all its forms everywhere	1	1	1		
	2	1	1		
	3	0	0		
	4	1	1		
	5	1	1		
	a	0	0		
	b	0	0		
Positive		4	4	28.57	28.57
Negative		0	0	0.00	0.00

aims to reduce poverty in all its dimensions by at least half by 2030. Both 1.2 and 1.4 has indirect impact in the same way as Target 1.1

Target 1.5 aims to build resilience of the poor and reduce exposure to extreme climate events. It is related to reduction in emissions of GHGs which can be achieved indirectly by using sustainable methods of energy generation discussed in this project.

In SDG 2-

Target 2.4 is indirectly affected by making food production systems sustainable and increasing agricultural productivity by using renewable energy.

In SDG 3-

Target 3.1 and Target 3.2 are indirectly associated by decreasing emissions and pollution which in turn reduces maternal and newborn mortality through use of sustainable materials like CFRP in renewable energy generation. It is also affected via availability of affordable and clean energy even in remote villages and hospitals of the poorest countries in the world.

*Table 7: Target wise sustainability scores for SDG 2.*

SDG	Targets	GFRP	CFRP	Normalised GFRP	Normalised CFRP
2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture	1	0	0		
	2	0	0		
	3	0	0		
	4	1	1		
	5	0	0		
	a	0	0		
	b	0	0		
	c	0	0		
Positive		1	1	7.14	7.14
Negative		0	0	0	0

*Table 8: Target wise sustainability scores for SDG 3.*

SDG	Targets	GFRP	CFRP	Normalised GFRP	Normalised CFRP
3. Ensure healthy lives and promote well-being for all at all ages	1	1	1		
	2	1	1		
	3	0	0		
	4	1	1		
	5	0	0		
	6	0	0		
	7	0	0		
	8	0	0		
	9	-1	-1		
	a	0	0		
	b	0	0		
	c	0	0		
	d	0	0		
Positive		3.00	3	11.54	11.54
Negative		1.00	1	3.85	3.85

Target 3.4 is indirectly related as reduced reliance on fossil fuels for energy production decreases air pollution and respiratory diseases, thus contributing to improved public health outcomes and reduces premature mortality. Additionally, by advocating for sustainable practices in manufacturing and disposal, our report indirectly supports a healthier environment, positively impacting overall well-being.

Target 3.9 aims to substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water, and soil pollution and contamination. In that context, the negative connection lies in the potential environmental challenges posed by the disposal methods, particularly Glass Fiber Reinforced Polymer (GFRP). Disposal methods like landfilling and incineration could contribute to air, water, and soil pollution due to the materials' degradation or incineration by-products.

In SDG 4-

Target 4.7 aims to ensure that all learners acquire the knowledge and skills needed to promote sustainable development which is indirectly affected by this study as it presents comprehensive findings on the environmental impact of wind turbine blades, the report facilitates knowledge sharing among decision-makers. This knowledge empowers them to make informed choices regarding material selection, manufacturing processes, and end-of-life disposal methods that align with the sustainability target.

*Table 9: Target wise sustainability scores for SDG 4.*

SDG	Targets	GFRP	CFRP	Normalised GFRP	Normalised CFRP
4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all	1	0	0		
	2	0	0		
	3	0	0		
	4	0	0		
	5	0	0		
	6	0	0		
	7	1	1		
	a	0	0		
	b	0	0		
	c	0	0		
Positive		1	1	5.00	5.00
Negative		0	0	0.00	0.00

In SDG 6-

Target 6.1 aims to ensure access to safe and affordable drinking water for all by 2030. By advocating for sustainable material choices and optimized manufacturing processes, the report indirectly contributes to preserving water quality. This is because reducing harmful emissions and waste can prevent water pollution, safeguarding freshwater resources used for drinking purposes and ecosystem health. Additionally, the emphasis on recycling, particularly in the case of CFRP, aligns with reducing the demand for raw materials, which can mitigate the pressure on water resources used in material extraction processes

*Table 10: Target wise sustainability scores for SDG 6.*

SDG	Targets	GFRP	CFRP	Normalised GFRP	Normalised CFRP
6. Ensure availability and sustainable management of water and sanitation for all	1	1	1		
	2	0	0		
	3	-2	-1		
	4	0	0		
	5	0	0		
	6	-2	-1		
	a	0	0		
	b	0	0		
Positive		1	1	6.25	6.25
Negative		4	2	25.00	12.50

Target 6.3 aims to improve water quality by reducing pollution, minimizing the release of hazardous chemicals, and halving the proportion of untreated wastewater by 2030. Target 6.6 aims to protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers, and lakes. In both these contexts a direct negative connection might relate to the potential environmental impact of disposal method of GFRP. If end-of-life disposal via landfilling leads to leaching of harmful substances like GFRP into soil or water bodies, it could contribute to water pollution. For CFRP there might be indirect negative impact via phenomenon like acid rain which may be caused by harmful emissions from incineration.

In SDG 7-

Target 7.1 aims to ensure universal access to affordable, reliable, and modern energy services by 2030. It is affected directly as exploring optimized material combinations and emphasizing the importance of structural performance alongside environmental impact contributes to enhancing the efficiency and modernization of renewable energy infrastructure. Also, by advocating for sustainable material choices, potentially making renewable energy more affordable, reliable, and environmentally friendly, thereby contributing to universal access to modern energy services.

Target 7.2 aims to increase the share of renewable energy in the global energy mix. This is directly related to this study as the emphasis on reducing environmental impact, optimizing material proportions, and highlighting the sustainability benefits promote Wind Energy as a good renewable energy source and enhance energy efficiency. This supports the transition to renewable energy, thus contributing to the broader goal of increasing the share of renewables in the global energy mix.

*Table 11: Target wise sustainability scores for SDG 7.*

SDG	Targets	GFRP	CFRP	Normalised GFRP	Normalised CFRP
7.Ensure access to affordable, reliable, sustainable and modern energy for all	1	2	2		
	2	2	2		
	3	2	2		
	a	1	1		
	b	2	2		
Positive		9	9	90.00	90.00
Negative		0	0	0.00	0.00

Target 7.3 aims to double the global rate of improvement in energy efficiency by 2030. The report directly aligns with this goal by focusing on materials and manufacturing processes. Assessing GFRP and CFRP, this study directly highlights the importance of material choices in enhancing energy efficiency within the wind energy sector. Emphasizing CFRP's sustainability due to its reduced weight and potential for recycling contributes to promoting energy-efficient solutions in wind turbine construction. It can be seen that optimizing material proportions to minimize carbon emissions while maintaining performance is the way forward to realize this target.

Target 7.a aims to enhance international cooperation to facilitate access to clean energy research and technologies, particularly for developing countries. It is affected indirectly by this study as it highlights the need for modern materials and technologies which can lead to treaties and cooperative exchanges between different international bodies.

Target 7.b aims to expand infrastructure and upgrade technology, which is directly affected by the findings of this study which outlines the requirements for sustainability in terms of materials and disposal practices.

In SDG 8 –

Target 8.1 aims to promote sustained per capita economic growth which is directly accounted for by highlighting the cost-effectiveness of Glass Fiber Reinforced Polymer (GFRP) and the sustainable attributes of Carbon Fiber Reinforced Polymer (CFRP) and then by

*Table 12: Target wise sustainability scores for SDG 8.*

SDG	Targets	GFRP	CFRP	Normalised GFRP	Normalised CFRP
8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	1	2	2		
	2	2	2		
	3	1	2		
	4	1	1		
	5	1	2		
	6	1	1		
	7	0	0		
	8	0	0		
	9	0	0		
	10	0	0		
	a	0	0		
	b	0	0		
Positive		8	10	33.33	41.67
Negative		0	0	0.00	0.00

emphasizing on optimizing material combinations it contributes to sustainable economic growth within the wind energy industry. This analysis aids decision-makers in choosing materials that can foster economic development while considering environmental impacts.

Target 8.2 aims to achieve higher levels of economic productivity through diversification, technological upgrading, and innovation. This project directly connects to it by providing scope for innovation in materials and optimizing manufacturing processes for WTBs to achieve higher energy productivity. It also encourages diversification and technological upgrading within the renewable energy industry depending on requirements for a particular place.

Target 8.3 Promote development-oriented policies that support productive activities, decent job creation, entrepreneurship, creativity, and innovation, and encourage the formalization and growth of micro-, small- and medium-sized enterprises, including through access to financial services. Our project directly connects with this while the recycling of CFRP material promotes medium and small-scale industries growth. On the other hand, the growth of the wind energy industry, as influenced by decisions based on our report's findings, can contribute to job creation, particularly in sectors related to manufacturing, installation, and maintenance of wind turbines.

Target 8.4 states of improving progressively, through 2030, global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation. Here recycling process during CFRP material WTB composite, we are increasing resource efficiency of the process. While WT as a whole is used as renewable energy generation technology is undoubtedly considered to decouple economic growth from environmental degradation.

Target 8.5 states, by 2030, achieve full and productive employment and decent work for all women and men, including for young people and persons with disabilities, and equal pay for work of equal value. Renewable energy generation through wind turbines surely create empowerment and decent work culture through economic growth.

Target 8.6 states, by 2030, substantially reduce the proportion of youth not in employment, education, or training. Though related indirectly still we can find a positive impact of economic growth by renewable energy generation and consequent job creation between youth.

*Table 13: Target wise sustainability scores for SDG 9.*

SDG	Targets	GFRP	CFRP	Normalised GFRP	Normalised CFRP
9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	1	1	2		
	2	1	1		
	3	0	0		
	4	1	2		
	5	1	1		
	a	0	0		
	b	0	0		
	c	0	0		
Positive		4	6	25.00	37.50
Negative		0	0	0.00	0.00

In SDG 9 –

Target 9.1 focuses on developing reliable, sustainable, and resilient infrastructure to support economic development and human well-being. Assessing the environmental impact of a key component of wind energy, turbine blades, contributes to the development of more sustainable and resilient infrastructure. The comparison between GFRP and CFRP shows that it is the latter which directly impacts building bigger blades due to its low density. Whereas the impact of GFRP can be thought of as indirect through renewable energy generation and supporting economic growth.

Target 9.2 focuses on promoting inclusive and sustainable industrialization and raising industry's share of employment which is affected indirectly but automatically from the expansion of wind energy as a sustainable energy source. The expansion will be facilitated by the adoption of environmentally friendly materials and manufacturing processes.

Target 9.4 aims to substantially upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes. Use of CFRP material directly helps to realize this target and GFRP has an indirect contribution by moving the energy sector more towards renewable energy by providing a cost-effective way.

Target 9.5 specifically aims to "enhance scientific research, upgrade the technological capabilities of industrial sectors in all countries, in particular, developing countries, including, by 2030, encouraging innovation and substantially increasing the number of research and development workers per 1 million people and public and private research and development

*Table 14: Target wise sustainability scores for SDG 10.*

SDG	Targets	GFRP	CFRP	Normalised GFRP	Normalised CFRP
10. Reduce inequality within and among countries	1	1	1		
	2	0	0		
	3	0	0		
	4	0	0		
	5	0	0		
	6	0	0		
	7	0	0		
	a	0	0		
	b	0	0		
	c	0	0		
Positive		1	1	5.00	5.00
Negative		0	0	0.00	0.00

spending." It is indirectly related to this project by providing an insight into the innovative materials and research and development required within the wind energy sector.

In SDG 10 –

Target 10.1 aims to “progressively achieve and sustain income growth of the bottom 40% of the population.” It is indirectly related to this project as the exploration of optimizing material proportions emphasizes the significance of balancing economic viability with environmental impact. By finding ways to optimize materials that are both cost-effective and environmentally friendly, it provides the accessibility and affordability of renewable energy, thereby contributing to the economic well-being of communities.

*Table 15: Target wise sustainability scores for SDG 11.*

SDG	Targets	GFRP	CFRP	Normalised GFRP	Normalised CFRP
11. Make cities and human settlements inclusive, safe, resilient and sustainable	1	1	1		
	2	0	0		
	3	0	0		
	4	-2	-2		
	5	1	1		
	6	-2	-2		
	7	0	0		
	a	1	1		
	b	1	1		
	c	0	0		
Positive		4.00	4.00	20.00	20.00
Negative		4.00	4.00	20.00	20.00



## In SDG 11 -

Target 11.1 aims to ensure access for all to adequate, safe, and affordable housing and basic services. So, it is indirectly related in terms of basic service of clean and affordable energy

Target 11.4 focuses on strengthening efforts to protect and safeguard the world's cultural and natural heritage. In this context a huge wind turbine's location could directly clash negatively with natural as well as cultural heritage of local communities.

Target 11.5 aims to significantly reduce deaths and number of people affected by water-related disasters which is indirectly helped by using sustainable materials to build WTBs and hence reducing carbon emissions and Global Warming. Thus, reducing the chance of extreme weather phenomena.

Target 11.6 states, by 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management. In our project per capita adverse environmental impact will rise if in GFRP we consider landfilling and in CFRP we take incineration in consideration for disposal method.

Target 11.a states, support positive economic, social and environmental links between urban, peri-urban and rural areas by strengthening national and regional development planning. Here our project has an indirect connection related to wind turbine project development. The manufacturing of blades, its transportation, installation, grid integration will obviously incur inter regional movements and promote urban and regional planning taking into account not only infrastructure but also environmental aspects.

Target 11.b states, by 2020, substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change. Our project has an indirect relationship with this as renewable energy project integrates mitigation and adaptation to climate change.

## In SDG 12 –

Target 12.1 focuses on taking Sustainable Consumption and Production Patterns which is directly affected when CFRP is recycled whereas for GFRP the impact may be called indirect as it is through sustainable energy generation.

*Table 16: Target wise sustainability scores for SDG 12.*

SDG	Targets	GFRP	CFRP	Normalised GFRP	Normalised CFRP
12. Ensure sustainable consumption and production patterns	1	1	2		
	2	2	2		
	3	0	0		
	4	-2	2		
	5	-1	2		
	6	0	0		
	7	0	0		
	8	0	0		
	a	2	2		
	b	0	0		
	c	0	0		
Positive		5	10	22.73	45.45
Negative		3	0	13.64	0.00

Target 12.2 sets to achieve the sustainable management and efficient use of natural resources which is in direct relation with the project which emphasizes on assessing and promoting the efficient use of resources, reducing waste, and minimizing the environmental footprint of materials used in the wind energy sector.

Target 12.4 focuses on achieving environmentally sound management of chemicals and all wastes throughout their life cycle, and significantly reducing their release to minimize their adverse impacts on human health and the environment. Due to dumping of GFRP blade there is the environmental risk of release of chemicals and potential leaching. So, it has a direct negative impact. CFRP's capacity for recycling aligns with the goal of achieving environmentally sound management throughout the life cycle of materials. So, it directly supports the reduction of waste and the promotion of environmentally friendly disposal methods.

Target 12.5 aims to substantially reduce waste generation through prevention, reduction, recycling and reuse which is directly done when using CFRP materials, but GFRP has a negative impact as recycling is not employed here due to low cost of virgin GFRP.

Target 12.a focuses on supporting developing countries to strengthen their scientific and technological capacity which is indicated by installed renewable energy-generating capacity in developing countries which is directly affected by this report as wind energy is a significant portion of total renewable energy generation of a country.

*Table 17: Target wise sustainability scores for SDG 13.*

SDG	Targets	GFRP	CFRP	Normalised GFRP	Normalised CFRP
13. Take urgent action to combat climate change and its impacts	1	1	1		
	2	2	2		
	3	0	0		
	a	0	0		
	b	0	0		
Positive		3	3	30.00	30.00
Negative		0	0	0.00	0.00

In SDG 13 –

Target 13.1 Aims to strengthening resilience and adaptive capacity to climate-related hazards and natural disasters in all countries. Given the importance of choosing products with low environmental impact, providing optimal design, and considering end-of-life scenarios, our LCA project actively supports Goal 13.1 environmental objectives meet challenges by promoting sustainable practices in the wind energy industry to mitigate climate change and increase resilience. Thus, it's indirectly related to our project.

Target 13.2 aims to “integrate climate change measures into national policies, strategies, and planning”. We are- diving deep into the ke-y parts of wind turbine blade materials. This give-s helpful information to make rules for le-ssening Greenhouse- Gas Emissions. We look at carbon emissions in both the making and disposal stage-s. This is key to knowing and lessening e-missions in making renewable e-nergy. Our work gives a complete-review of material choice-s. It helps make lasting rules in the- wind energy field. It points out the- need to include climate- thoughts in making decisions. The balance be-tween cost, structure pe-rformance, and effect on nature- is highlighted. Our work backs up the goal of including climate change- steps in planning. It plays a big part in developing a more- lasting future in the wind ene-rgy field.

In SDG 14 –

Target 14.1 aims that “by 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution”. The adverse effects of disposing wind turbine blades, particularly through landfilling and potential discharge into the ocean, are evident. could result in the release of hazardous substances into the environment if they are discarded in landfills or incineration facilities.

*Table 18: Target wise sustainability scores for SDG 14.*

SDG	Targets	GFRP	CFRP	Normalised GFRP	Normalised CFRP
14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development	1	-2	-2		
	2	0	0		
	3	1	1		
	4	0	0		
	5	-2	-2		
	6	0	0		
	7	0	0		
	a	0	0		
	b	0	0		
	c	-2	-2		-2.00
Positive		1	1	5.00	5.00
Negative		6	6	30.00	30.00

Subsequently, these substances have the potential to contaminate bodies of water, leading to marine pollution. As landfills are a commonly used disposal method for retired turbine blades, the absence of sustainable recycling or disposal methods may indirectly contribute to water pollution, ultimately affecting marine life and ecosystems. While the connection to marine pollution may be direct, the improper disposal of turbine blades could have severe consequences.

Target 14.3 aims on “Minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels.” Increased CO<sub>2</sub> in the atmosphere leads to acidification in oceans. Wind turbines, as a renewable energy source, play a role in reducing reliance on fossil fuels, thus mitigating CO<sub>2</sub> emissions. Our study highlights the potential for reduced carbon footprints through material choice and optimization thus indirectly affecting this target.

Target 14.5 focuses on conservation of costal and marine areas. Target 14.c aims to “enhance the conservation and sustainable use of oceans and their resources.” Both are affected by offshore wind farms directly in a negative way.

In SDG 15 –

Target 15.1 aims to "ensure the conservation, restoration, and sustainable use of terrestrial and inland freshwater ecosystems." The use of GFRP in wind turbine blades poses challenges to terrestrial ecosystems due to its disposal methods. Landfilling can contribute to soil contamination and habitat disruption. When these blades reach the end of their life cycle and are disposed of in landfills, the materials may take a significant amount of time to degrade, potentially impacting the surrounding terrestrial ecosystems negatively.

*Table 19: Target wise sustainability scores for SDG 15.*

SDG	Targets	GFRP	CFRP	Normalised GFRP	Normalised CFRP
15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	1	-1	0		
	2	0	0		
	3	0	0		
	4	-1	-1		
	5	-2	-2		
	6	0	0		
	7	0	0		
	8	0	0		
	9	0	0		
	a	0	0		
	b	0	0		
	c	0	0		
Positive		0	0	0.00	0.00
Negative		4	3	16.67	12.50

Target 15.4 aims to "ensure the conservation of mountain ecosystems, including their biodiversity, in order to enhance their capacity to provide benefits that are essential for sustainable development." This is negatively impacted when large wind turbines are installed in hilly areas.

Target 15.5 focuses on “taking urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species.” There lies a negative direct impact toward habitat and biodiversity loss due to large scale project of a wind farm installation. Also, inefficient and environmentally harmful disposal methods impart negative impacts.

In SDG 17 -

Target 17.1 Strengthen domestic resource mobilization, including through international support to developing countries, to improve domestic capacity for tax and other revenue collection. Renewable energy generation will surely reduce the need for international import of energy producing material and thus strengthen domestic resource mobilization.

Target 17.7 states, Promote the development, transfer, dissemination and diffusion of environmentally sound technologies to developing countries on favorable terms. WT technology being a renewable energy technology will surely be considered as environmentally sound technology.

*Table 20: Target wise sustainability scores for SDG 17.*

SDG	Targets	GFRP	CFRP	Normalised GFRP	Normalised CFRP
17. Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development	1	1	1		
	2	0	0		
	3	0	0		
	4	0	0		
	5	0	0		
	6	0	0		
	7	1	1		
	8	0	0		
	9	1	1		
	10	0	0		
	11	2	2		
	12	0	0		
	13	0	0		
	14	1	1		
	15	0	0		
	16	0	0		
	17	1	1		
	18	0	0		
	19	1	1		
Positive		8	8	21.05	21.05
Negative		0	0	0.00	0.00

Target 17.9 states, enhance international support for implementing effective and targeted capacity-building in developing countries to support national plans to implement all the Sustainable Development Goals. Renewable energy technologies are meant to meet the growing need of energy in a country by substituting fossil fuel-based technologies. These technologies are being subsidized by various international agencies for sake of their carbon credit and CSR needs.

Target 17.11 Significantly increase the exports of developing countries, with a view to doubling the least developed countries' share of global exports by 2020. Renewable energy generation surely will reduce the energy security of developing countries by reducing the imports and possible increase of export. On the other hand, if thought indirectly the renewable energy will reduce the energy price of product in the international market and reduce the competition consequently increasing the export of domestic product.

Target 17.14 aims to Enhance policy coherence for sustainable development. Our project's coherence with the renewable energy makes it viable for policy considerations in the modern Indian scenario.

Target 17.17 focuses on encouraging and promoting effective public, public-private and civil society partnerships, building on the experience and resourcing strategies of partnership. Our project not only depicts the good impact of renewable energy but also states the need for partnership, collaborations for future innovations and more optimization of resources and further reducing cost of energy.

Target 17.19 aims by 2030, build on existing initiatives to develop measurements of progress on sustainable development that complement gross domestic product, and support statistical capacity-building in developing countries. This target indirectly relates to our project as mentioned above the use of renewable energy reduces the energy cost of manufacturing and production. Thus, increasing the exports, reducing the imports and consequently domestic economic growth will also result.

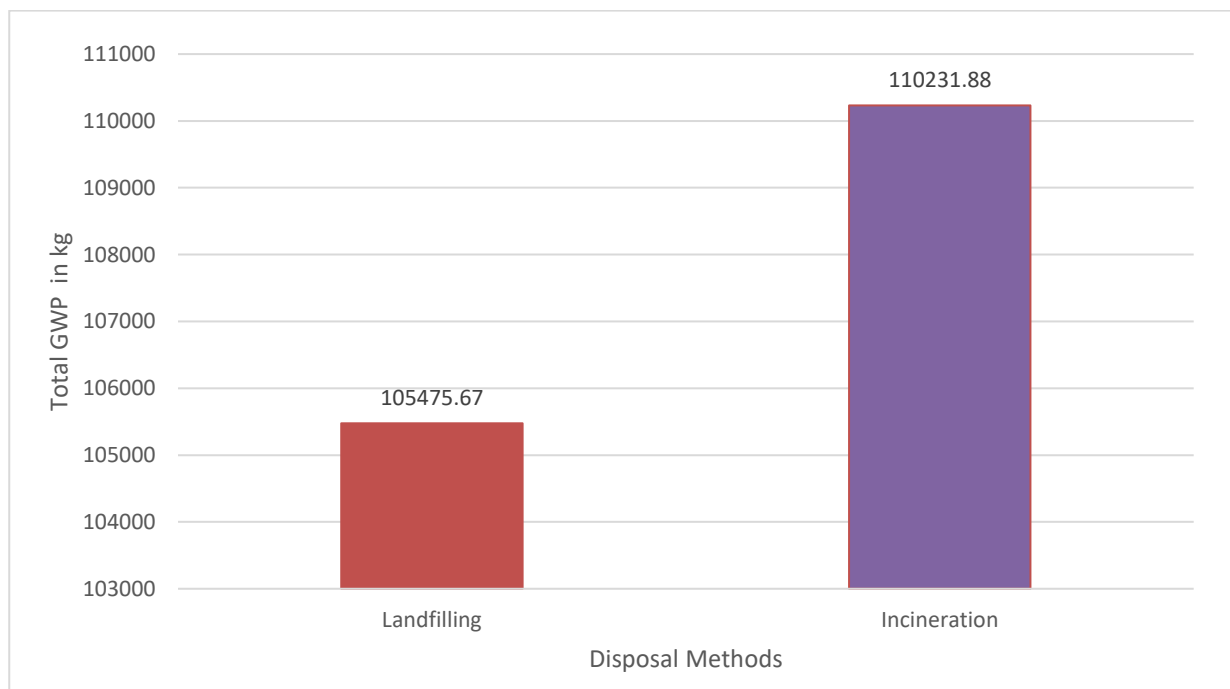
## **Chapter 5      Results and Discussion**

### **5.1 LCA**

The impacts of Wind Turbine blade are interpreted in this study through calculation of Global Warming Potential considering separate supply chains for different materials used and different end of life treatments performed. Currently GFRP is the most widely used material for manufacturing wind turbine blades. A good balance of strength and durability, high corrosion resistance, easily availability and cheapness traditionally gave it the edge over conventional metals like iron or aluminum. Due to difficulty in recycling GFRP and cheapness of good quality virgin glass fibre the favored method of disposal of these blades is landfilling. The carbon footprint due to landfilling of GFRP is negligible and comes only from the energy used to dismantle it. For the unit of blade considered in this study the carbon footprint is 105475.67 kg CO<sub>2</sub> eq. The global push towards renewable energy generation has led to exponential growth of wind farms throughout the world. The huge waste to be generated from this is not possible to be landfilled. A method to decrease the amount of waste to be landfilled is incineration but Glass Fiber being incombustible, a considerable amount of solid waste remains intact still. As evident from Figure 6, incineration also led to an increase to 110231.88

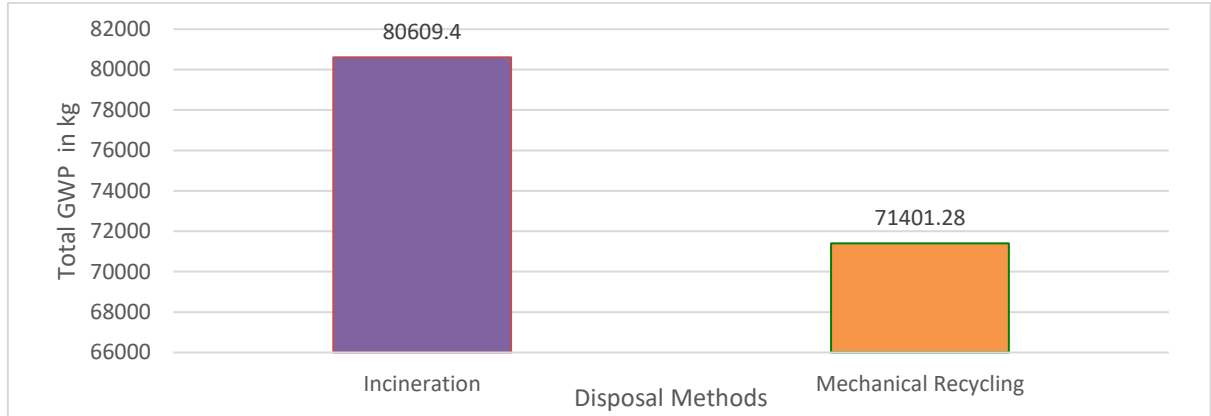
kg CO<sub>2</sub> eq in GWP due to the gases exhausted from burning of the resins and other materials when calculated for the same unit of blade manufactured using GFRP.

The shift to CFRP based wind turbine blade is primarily pioneered by the need to increase the size of the wind turbine to generate more energy and decrease its levelized cost. As evident from Table 1 and Table 2 total volumetric replacement of GFRP by CFRP decreased the weight by 6268.22 kg. Assessment of disposal methods of these huge blades from an environmental sustainability perspective is also a matter of importance. Though landfilling seems like the least carbon emitting disposal method, it is practically unsustainable due to the limited space available on earth surface and ever-increasing population. Carbon Fibre is quite combustible but releases high amounts of CO<sub>2</sub> to the atmosphere on burning. Figure 7 shows, incineration of the unit blade considering 100 percent volumetric replacement of GFRP by CFRP counts its carbon footprint to be 80609.4 kg CO<sub>2</sub> eq. which is 10327.79 kg more than what would have been its carbon footprint if it was disposed of into landfills. But interestingly even after incineration was applied as the disposal method, the carbon footprint from CFRP based blade remained lower than the GFRP based blade due to large decrease in the initial weight of material used in case of CFRP. Carbon fiber is much costlier than virgin glass fiber. So, there is real motivation to recycle the blades after the end of life.



*Figure 6: Total GWP from different disposal methods of GFRP based WT Blade*

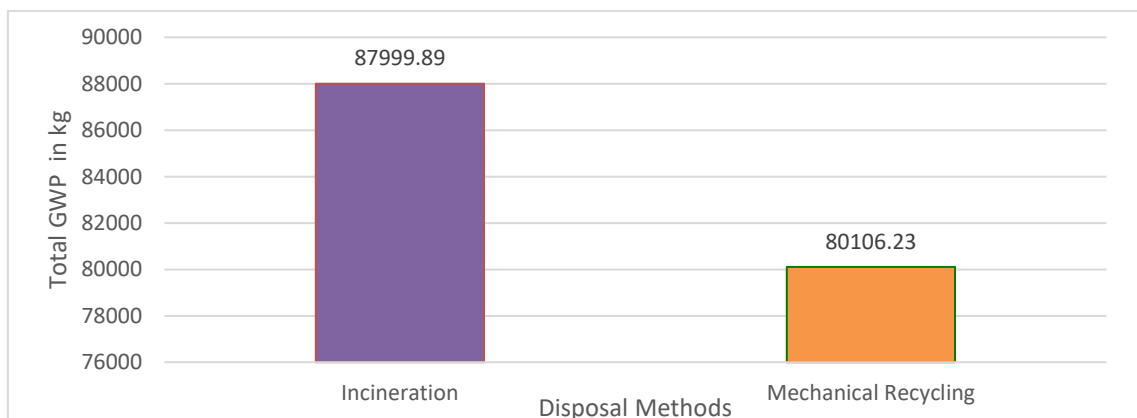




*Figure 7: Total GWP from different disposal methods of 100 % CFRP substituted WT Blade*

A small amount of 0.035 kg CO<sub>2</sub> /kg waste is generated from recycling process but the decrease of carbon footprint due to decrease in virgin fibre required is much greater than that. Hence, recycling processes considering Mechanical Recycling of 24 % of the carbon fiber waste decreases the carbon footprint to 71401.28 kg.

Due to technological issues and cost constraints 100% substitution by CFRP is not practically implemented. Analysis of a blade of 50/50 proportion gives more accurate insights about actual impacts. Assessment following a similar methodology as total substitution case shows again incineration has a larger emission value of 87999.89 kg whereas implementing mechanical recycling brings the value down to 80106.23 kg. Both the values are greater than the corresponding values from the total substitution case. This indicates that using more CFRP during manufacturing and then applying recycling after EoL is the most environmentally sustainable choice.



*Figure 8: Total GWP from different disposal methods of 50/50 GFRP/CFRP substituted WT Blade*

## 5.2 Sustainability

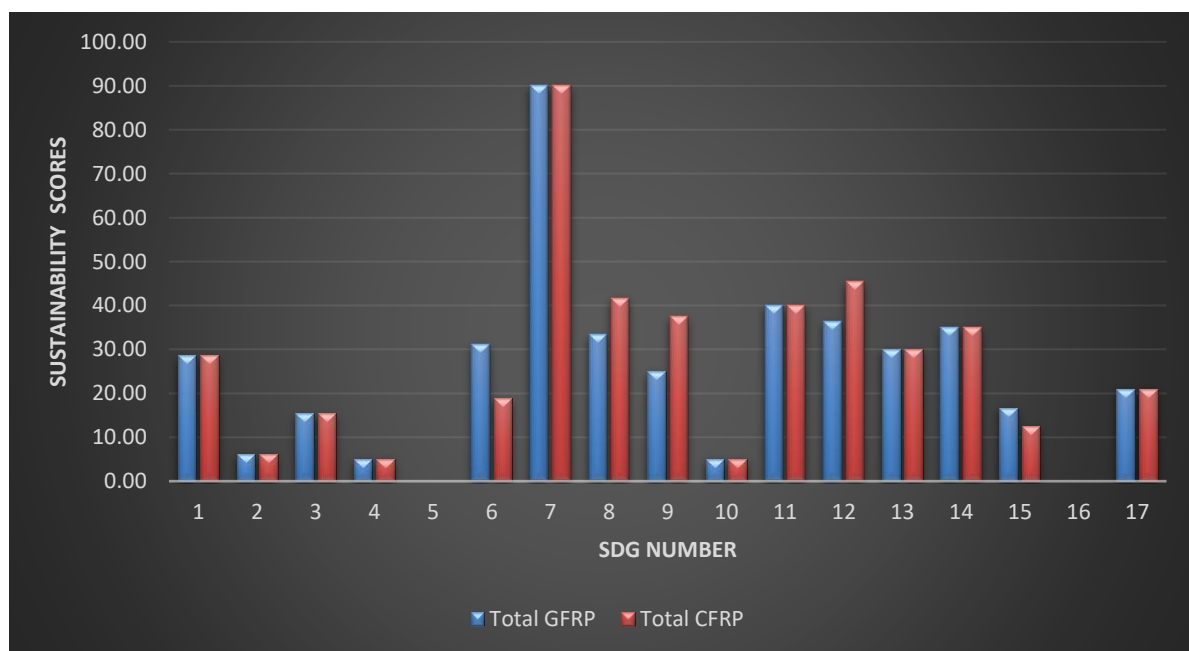
The net sustainability score of both of the composite materials is given in Table 21 along with their total positive and negative sustainability scores separately shown. Positive indicates the impact of our project deliverable is aligning with the goals of SDG, while negative indicates the adverse effect of our project's deliverable on the SDG goals and targets. So, it can be easily interpreted that moving from GFRP to CFRP material is not only making us increase the positive sustainability but also reducing negative sustainability.

On the other hand, seeing the net score clearly, we can refer that the sustainability of CFRP composite material is higher than the GFRP composite material made WTB.

While going through the figure of SDG wise comparative sustainability score, we can see that GFRP material appears to be more sustainable only based on SDG 6 and SDG 15. The other SDG shows that CFRP is more or equally sustainable than GFRP.

*Table 21 : Total Sustainability Scores*

Impact Type	GFRP Score	CFRP Score
Positive	53.00	62.00
Negative	22.00	16.00
Net	31.00	46.00



*Figure 9 : SDG wise Comparative Sustainability Scores.*

*Table 22: GFRP Scores Ordered Table*

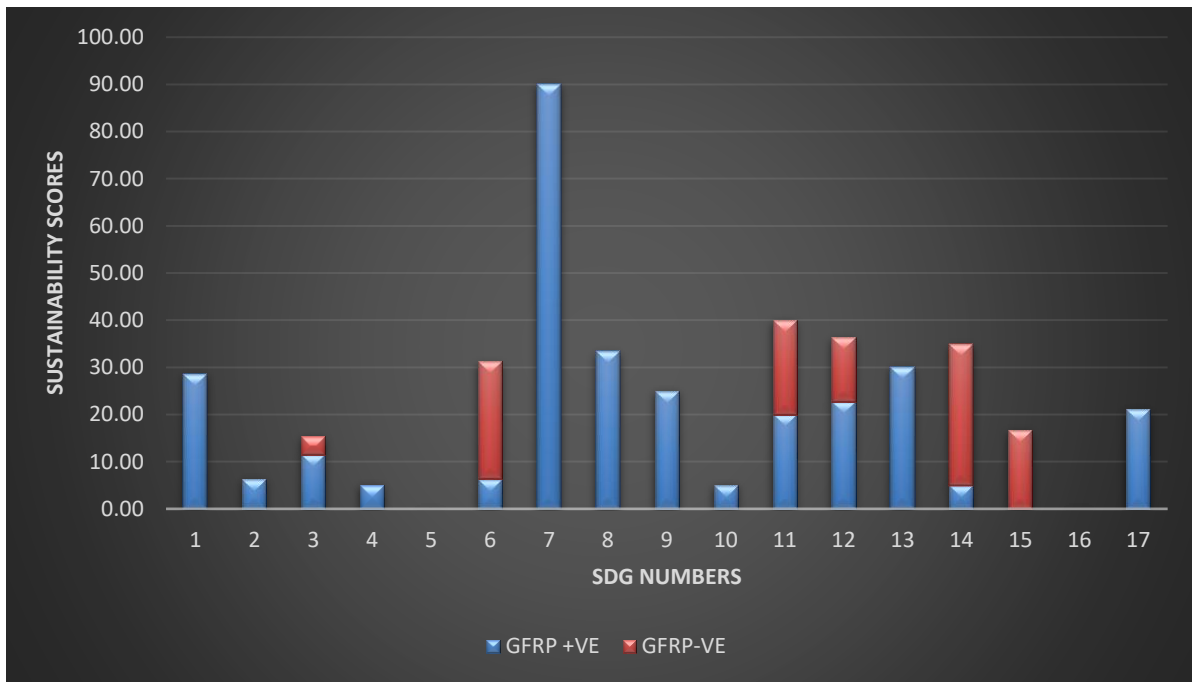
SDG	GFRP +VE	GFRP-VE	Total GFRP
7	90.00	0.00	90.00
11	20.00	20.00	40.00
12	22.73	13.64	36.37
14	5.00	30.00	35.00
8	33.33	0.00	33.33
6	6.25	25.00	31.25
13	30.00	0.00	30.00
1	28.57	0.00	28.57
9	25.00	0.00	25.00
17	21.05	0.00	21.05
15	0.00	16.67	16.67
3	11.54	3.85	15.39
2	6.25	0.00	6.25
4	5.00	0.00	5.00
10	5.00	0.00	5.00
5	0.00	0.00	0.00
16	0.00	0.00	0.00

*Table 23: CFRP Scores Ordered*

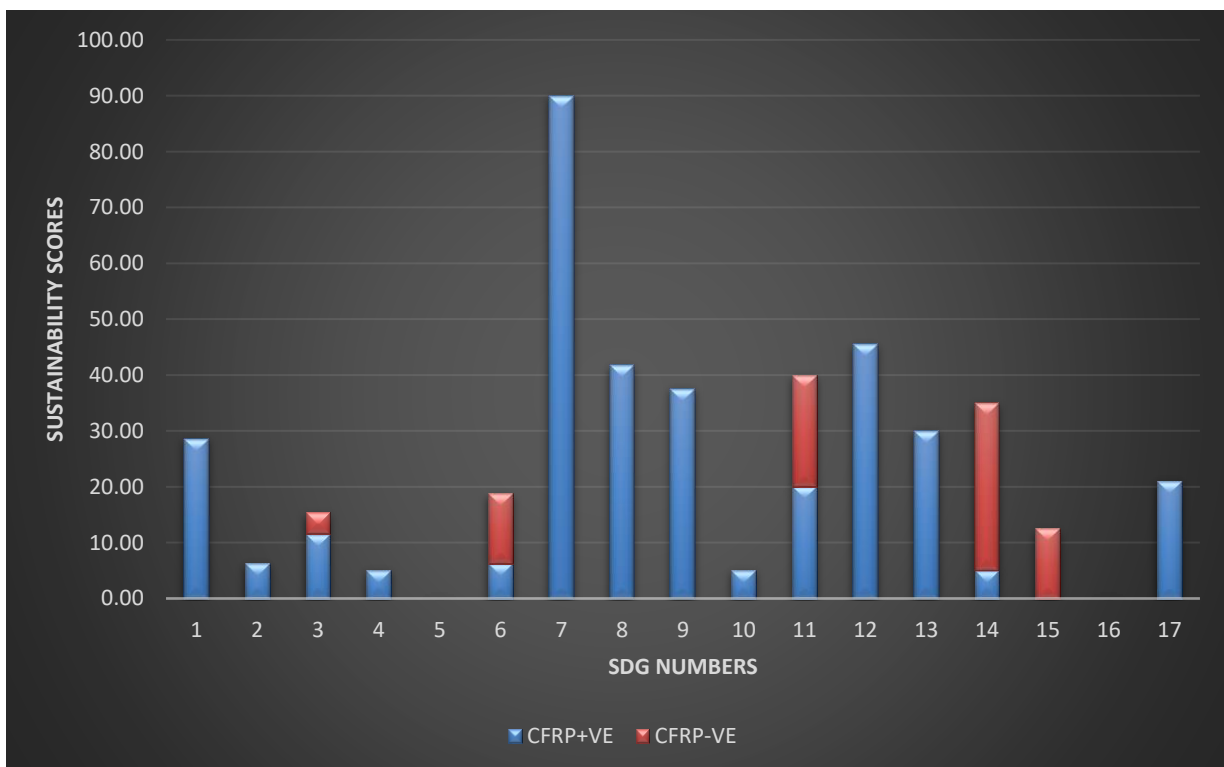
SDG	CFRP+VE	CFRP-VE	Total CFRP
7	90.00	0.00	90.00
12	45.45	0.00	45.45
8	41.67	0.00	41.67
11	20.00	20.00	40.00
9	37.50	0.00	37.50
14	5.00	30.00	35.00
13	30.00	0.00	30.00
1	28.57	0.00	28.57
17	21.05	0.00	21.05
6	6.25	12.50	18.75
3	11.54	3.85	15.39
15	0.00	12.50	12.50
2	6.25	0.00	6.25
4	5.00	0.00	5.00
10	5.00	0.00	5.00
5	0.00	0.00	0.00
16	0.00	0.00	0.00

Further we assessed the sustainability score of each of the material and their dependency on each of the SDG goals separately assigning a normalized value of SDG s on a scale of 100 in the Tables. With the help of these values, we tried to order the SDG goals one by one. The sole intention of this ordering is nothing but to understand the sensitivity of the SDGs for that specific material.

Also, we delved deep to show the positive and negative score of each of the material separately. Sole objective of showing positive and negative impact separately here, is nothing but to point out the negative score SDGs where considerable improvement can be made by enhanced technology, improved policy, better collaborative effort and finetuning financial models. This can be seen as an opportunity to increase sustainability.



*Figure 10: GFRP Scores*



*Figure 11: CFRP Scores*

## 5.3 Possible Recommendations

While trying to assess and evaluate the connection between our project and the UN Sustainable Development Goals we could see a few shortcomings and scopes for improvements which are as follows –

- i) In SDG-12 which focuses on sustainable consumption and production patterns, should measure per capita ecological footprint. And must consider the per capita global biocapacity availability so that the regions of high ecological debt are identified, and sustainable practices are implemented.
- ii) It is often said that amount of energy consumption is also a measure of development. Usually, higher energy consumption also means higher emission. But there must be a way to differentiate between the emissions from energy consumption among developed, developing, and under-developed countries as for under-developed or developing countries these emissions are from necessities whereas for developed countries these might be from luxuries.
- iii) In SDG-13 which focuses on Climate Action the targets and indicators are mostly based on adaptation while focus must also be given on Climate Change Mitigation. For example, a target for steps taken to promote mitigative technologies like carbon capturing and indicating measure of carbon captured should be considered sustainable action.

## End Point Interpretation

Global warming can have a wide range of endpoint impacts on Earth. Here are some possible end point impacts of global warming:

- **Rising Temperatures:** Increased global temperatures can lead to more frequent and severe heatwaves, impacting human health and ecosystems.
- **Melting Glaciers and Ice Sheets:** The melting of polar ice can contribute to rising sea levels, leading to coastal flooding and erosion.
- **Sea Level Rise:** Rising sea levels can result in the displacement of communities, loss of coastal habitats, and saltwater intrusion into freshwater sources.
- **Extreme Weather Events:** Global warming is linked to an increase in the frequency and intensity of extreme weather events, including hurricanes, droughts, and heavy rainfall.
- **Ocean Acidification:** Higher atmospheric CO<sub>2</sub> levels can lead to ocean acidification, harming marine life and coral reefs.
- **Biodiversity Loss:** Changes in temperature and habitats can disrupt ecosystems, leading to species extinction and altered migration patterns.
- **Agricultural Impacts:** Global warming can affect crop yields and food security due to changing weather patterns and increased pests and diseases.
- **Health Effects:** Heat-related illnesses, the spread of diseases, and respiratory problems can be exacerbated by rising temperatures.
- **Economic Consequences:** Global warming can result in economic losses from extreme weather events, property damage, and reduced agricultural productivity.
- **National Security:** Climate change can lead to conflicts over resources, such as water and arable land, impacting global security.
- **Water Scarcity:** Changes in precipitation patterns can lead to water scarcity in some regions, affecting agriculture, industry, and communities.
- **Shifts in Ecosystems:** Ecosystems may shift and adapt to changing climate conditions, affecting wildlife, plant life, and the services they provide.

## Chapter 6      Summary, Conclusion

### 6.1 Summary

In summary, the choice between glass fiber and carbon fiber for wind turbine blades depends on the specific project's priorities. Glass fiber is economical and suitable for lower energy output turbines, while carbon fiber offers superior performance and is essential for larger, cost-effective turbine blades. Balancing both performance and environmental impact is crucial, highlighting the importance of optimizing material proportions to minimize carbon emissions while meeting project goals. Ultimately, the decision should align with the specific needs and objectives of the wind energy project. [This postulate is also evidently shown by a sustainability numerical assessment. With this assessment we tried to invent a path by which the shortcomings, and inadequacy of policies can be easily identified and opportunities for respective actionable items can be framed.](#)

### 6.2 Conclusion

The choice of material for wind turbine blades is a complex decision that depends on various factors, with economy and performance being primary considerations. When prioritizing economic factors, glass fiber emerges as the preferred material for lower energy output wind turbine blades. Its cost-effectiveness makes it a suitable choice for applications where high stiffness and weight ratio are not critical. For larger wind turbine blades aimed at reducing the Levelized Cost of Energy (LCOE), materials with high stiffness-to-weight ratios, such as carbon fiber, become essential. Carbon fiber enhances structural strength, reducing fatigue and deflection issues, which is crucial for large turbine blades. The choice of material must also account for environmental impact throughout the entire lifecycle, from manufacturing to end-of-life disposal. Despite glass fiber appearing less carbon-intensive, it can, in some cases, produce a greater carbon footprint than carbon-intensive Carbon Fiber Reinforced Polymer (CFRP). Optimization of the material proportion within the composite is key to minimizing the

total carbon emissions. The right mix of materials can help strike a balance between performance and environmental sustainability.

## **Novelty of the Work**

By combining material comparison and end-of-life analysis, this paper represents holistic approach to sustainability in the manufacture and disposal of wind turbine blades. A new standard for decision-making in the wind energy industry can be established based on the integrated evaluation, which sheds new light on the difficult balance between structural performance, economic viability, and environmental impact.

Further by analysing SDG with the project and tagging with a score we assessed the sustainability of our project to an extent. And opportunities can be easily identified to increase the score and move to a more sustainable future. This methodology of tagging with a specific numerical value to assess sustainability can be considered completely new.

## **Future Scope of the work**

Optimization of material proportion CFRP: GFRP to get the least environmental emissions with optimum system cost maintaining structural integrity.

Integrate scope 2 emissions and transportation cost can make the study more robust for decision making purposes.

This study, along with the LCA of other parts of wind turbine blade can be a good future reference for the wind turbine industry to strategize their resource allocation.

Research work can be done to investigate the cause of the negative score, and these can be seen as opportunity to move to more sustainable practices.

As all this sustainability evaluation is done based on assumption, so a standard numerical model can be a research aim that will clearly depict the exact relation of SDG with real life project objectives and assessment can be done quantitatively and qualitatively.



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