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Comparative Environmental and Economic Assessment of Wind Turbine Blade Materials

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Abstract

Wind energy has proven to be one of the most stable and non-polluting renewable energy sources to mass power production. For energy production wind turbine is an essential part of the wind power plant. The choice of the blade material and coating applied on it has a strong impact on aerodynamic performance, mechanical strength, fatigue life, manufacturing possibility, and environmental effects throughout the operating life of the turbine. Hence, authors have attempted to perform the comparative analysis using MATLAB/SIMULINK and include performance, costing, sustainability analysis, along with carbon emission analysis of the five recently developed material combinations i.e. Glass Fiber Reinforced Polymer (GFRP) with Polyurethane, CFRP with Composite, Steel with Epoxy, Aluminium Alloy with Fluoropolymer, and Wood Epoxy with Polyurethane for operating scenario of average wind speed. The findings have shown that despite the superior stiffness-to-weight ratio and aerodynamic performance of the CFRP-based blades, they have the most negative impact on the environment with the yearly carbon emissions of 3321.98 tons mostly attributed to the energy-consumption manufacturing processes. Conversely the polyurethane covered wood-epoxy blade has the least carbon footprint of just 34.77 tons per annum and has a great cost savings. Implications of the findings are obvious, as material sustainability and not performance in itself should become one of the most important prerequisites in the design of next-generation wind turbine blades. The work can be of great help to researchers, manufacturers and policy makers who are interested in creating wind energy systems that balance efficiency, cost and environmental responsibility.

Keywords: Wind energy, wind turbine, turbine blade, sustainability, turbine material, clean energy

INTRODUCTION

Nowadays, due to widespread environmental awareness regarding the depletion of fossil fuels and their negative impact on the environment, customers are inclined towards cleaner forms of energy resources like solar, wind energy, etc. Renewable Energy Sources (RES) are the pathway to a sustainable future; however, RES has lower efficiency as compared to fossil fuel-based energy [1–4]. Wind Energy has become the backbone of RES by providing clean and sustainable solutions. After hydropower plants, wind energy is widely used for bulk production and transmission of electrical energy and wind energy.

Wind power plants have many components, but wind turbine has a significant role in generating electricity due to the effect of their aerodynamic performance which further depends upon the manufacturing of blade material [5–8].

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These plants enhance a clean environment and maintain economic feasibility. Turbine blade material directly affects the performance, carbon footprint, and sustainability of wind power plants. The correct, cost-effective, and efficient material must be selected for the turbine blade to ensure the environmental friendliness of the wind power plant and economic feasibility.

Recent advances in material science and engineering have increased the scope and spectrum of available options and thus enhanced the performance and sustainability of wind turbines [9–14].

With the rising transition from non-renewable to renewable energy sources, the selection of the right manufacturing material is the key point for successful transformation, both in respect of cost-effectiveness as well as environmental friendliness [15–19]. It has been observed that high-quality research on the comparative performance study of micro-turbines and small wind turbines on low wind speed applications has been conducted independently. Additionally, separate analyses of wind turbines with flexible and stiff blades, as well as those with vertical and horizontal axes, have been conducted. The past literature shows that each material has different properties that influence the overall performance characteristics of wind turbine systems [20–24].

Further, no clear comparative study has taken place focusing on the selection of materials along with their coating type concerning the overall performance characteristics of wind turbine systems in terms of power generation capacity, annual energy output, lifecycle CO_2 emissions, and overall blade costs. Therefore, the comparative investigation combinations for materials and coatings for designing wind turbines have been carried out by selecting the most applicable materials and energy outcomes. This research work assesses the performance of five recently developed material combinations for average wind speed.

The article is organized in this manner: the introduction section covers basic details of materials that have different properties that influence the overall performance characteristics of wind turbine systems and the objective of this study followed by the selection of material combinations at their coating types for average wind speed operation considered for the study, then system modeling has been performed using MATLAB/SIMULINK followed by the corresponding simulation results showing the best alternative out of five output performance combinations and finally, the comparative conclusion of this research work is summarised.

MATERIALS AND METHODS

This study involves MATLAB/SIMULINK-based simulations to evaluate the performance of five selected material combinations: wood epoxy with polyurethane, steel with epoxy, aluminum alloy with fluoropolymer, CFRP with composite, and glass fiber reinforced polymer (GFRP) with polyurethane. After this in-depth analysis, five ideal combinations of material and coating are selected as: GFRP + Polyurethane, CFRP + Composite Coating (PU/Epoxy), Steel + Epoxy, Aluminium Alloy + Fluoropolymer, Wood-Epoxy + PU Coating. The flowchart employed for this methodology is shown in Figure 1.

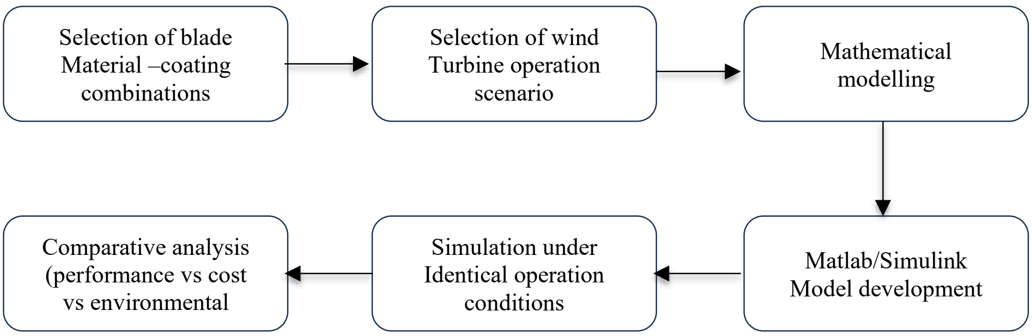

Figure 1. Methodology flowchart for comparative analysis.

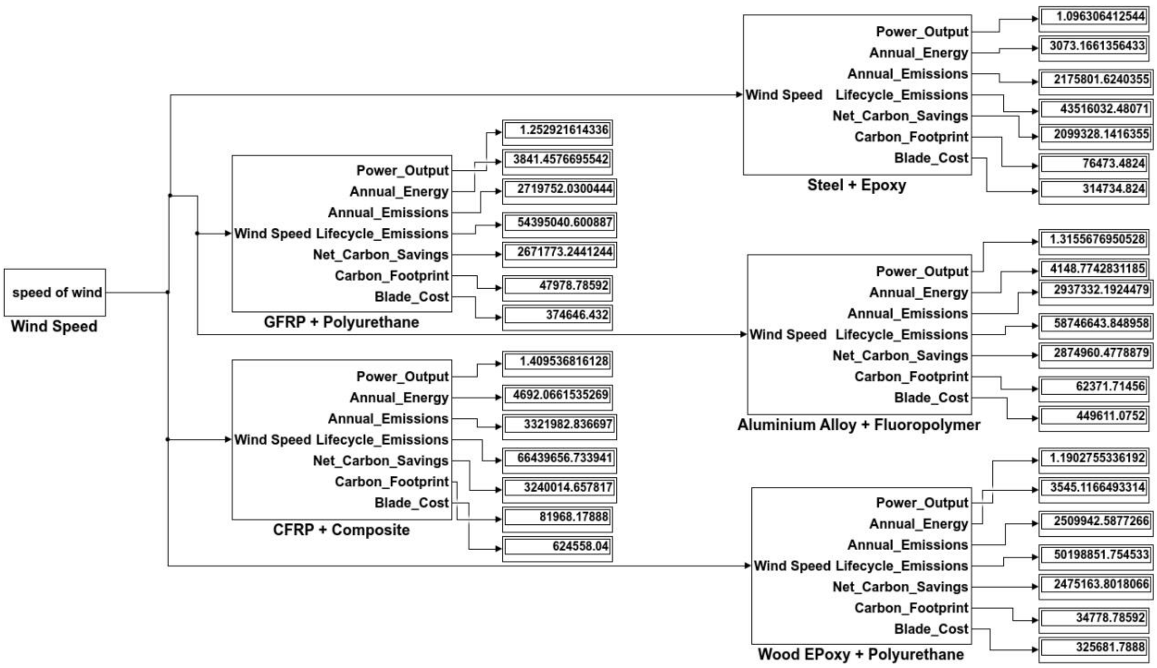

Figure 2. Average wind speed-based MATLAB SIMULINK model.

The considered parameters include an approximate swept area by blades of 10,000 m^2, power coefficients of all combinations ranging between 0.35 to 0.45, capacity factor which is below 40% for every combination, blade material cost varying between 3 to 25 \$/kg, blade mass depending upon material type, coating cost ranging between 15 to 25 \$/m^2, blade material carbon factor, coating carbon factor and available energy for each combination [2, 4, 6, 7, 13, 15].

System Modelling

The system modelling is accomplished in MATLAB/SIMULINK for average wind speed as shown in Figure 2. Separate Simulink blocks have been created to accomplish mathematical modelling for each combination, and wind speed is used as a common input for all combination models. Display box and Scope block have been used for viewing outputs in digital and graphical forms, respectively. Figure 2 shows the average wind speed-based MATLAB SIMULINK model.

The numerical solutions obtained for various parameters through simulations of Simulink model are presented in next section. Some of the mathematical relations implemented for numerical research analysis are as below:

$$\text{Power} = 1/2\ A\rho C p v^3 \quad (1)$$

$$\text{Annual Energy} = \text{Rated Power} \times \text{Capacity Factor} \times 8760 \quad (2)$$

$$\text{Annual Emission} = \text{Annual Energy} \times \text{Grid Emission Factor} \quad (3)$$

$$\text{Blade Cost} = (\text{Material cost} \times \text{Blade Mass}) + (\text{Coating cost} + \text{Surface Area}) \quad (4)$$

$$\text{Carbon Footprint} = (\text{Material carbon factor x Blade Mass}) + (\text{Coating carbon factor} + \text{Area}) \quad (5)$$

$$\text{Life Cycle Emission} = \text{Annual Energy} \times 20 \times \text{Grid Emission Factor} \quad (6)$$

SIMULATION RESULTS AND DISCUSSION

The performance of five typical material combinations is assessed in this study using simulations based on MATLAB/SIMULINK. Numerous factors, including power generating capacity, carbon emissions, manufacturing costs, and lifespan sustainability, are taken into consideration when determining the overall effectiveness of these materials and conducting a complete evaluation of material compatibility. Simulation results have been obtained for average wind speed operations of 8m/s or 18mph or 29 km/hr as shown in Figures 3 to 9.

To compare the performance of different material combinations, power output is one of important factor and the obtained simulation results for the same average wind speed is shown in Figure. 3. The results indicate that CFRP + Composite is the most efficient material in terms of power output, while Steel + Epoxy ranks the lowest. While the other three combinations present moderate power outputs, balancing performance. Material selection should account for power efficiency alongside other factors, such as environmental impact, lifecycle costs, and operational requirements, to achieve sustainable and effective wind energy solutions. The difference (performance gap) between the highest-performing material and the lowest-performing material is approximately 0.313 MW.

The energy output is a critical measure of the efficiency and performance of these materials in wind energy generation. Figure 4 illustrates the comparison of annual energy output for considered combinations. It is found that CFRP+ composite shows best profile and lowest output is counted for Steel + epoxy combo. On the other hand, a strong competition is given by Aluminium alloy + fluoropolymer. The difference of highest and lowest annual energy output of 1619 MWh highlights significant disproportions in material performance. For high demand projects the combination of CFRP + composite can be a better choice.

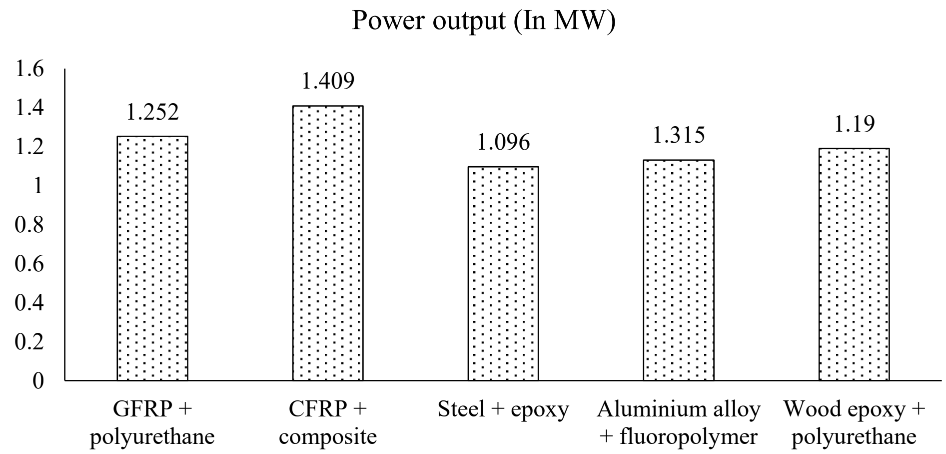

Figure 3. Power output comparison.

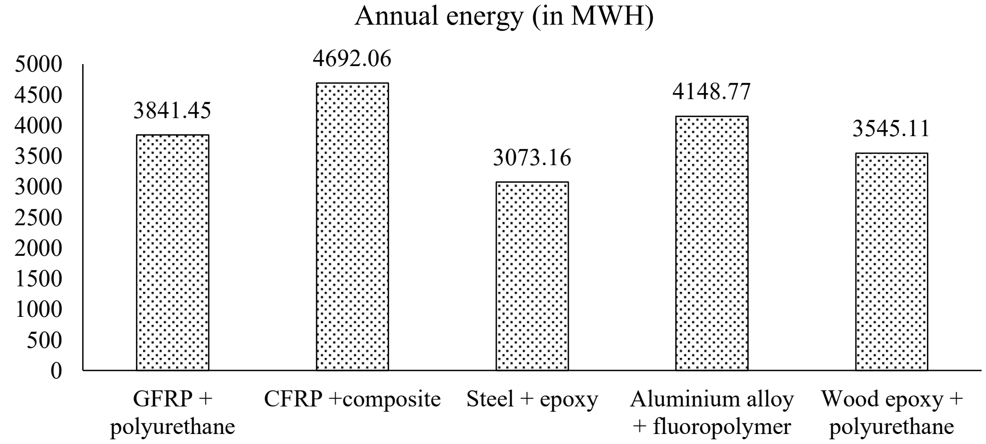

Figure 4. Annual energy comparison.

Comparison on basis of Annual CO_2 emissions is presented in Figure 5. where it shows the environmental impact of each material combination. The lowest CO_2 emissions is noted for Steel + Epoxy at 2175.8 tons, and thus the most environment friendly combo out of all. On the other side CFRP + composite combinations reports for highest annual emissions at 3321.98 tons. Performance gap of 1146 tons on annual basis emphasizes that the need for material selection should be made on basis of environmental impacts.

Carbon footprint (in tons) comparison is shown in Figure 6 for all five selected wind turbine blade material combinations. This comparison tells about environmental sustainability of different combinations for their corresponding manufacturing and operation. With highest footprint at 81.96 tons and the most impact making combination is CFRP + composite whereas Wood Epoxy + Polyurethane gives lowest carbon footprints at 34.77 tons. The considerable performance gap existing in these results shows the wide variability of the environmental performance for all selected materials.

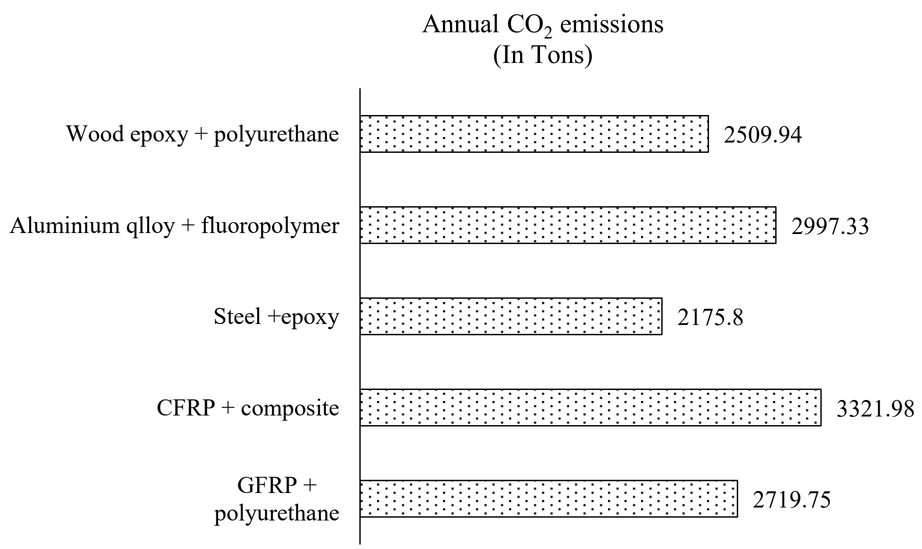

Figure 5. Annual CO_2 emissions comparison.

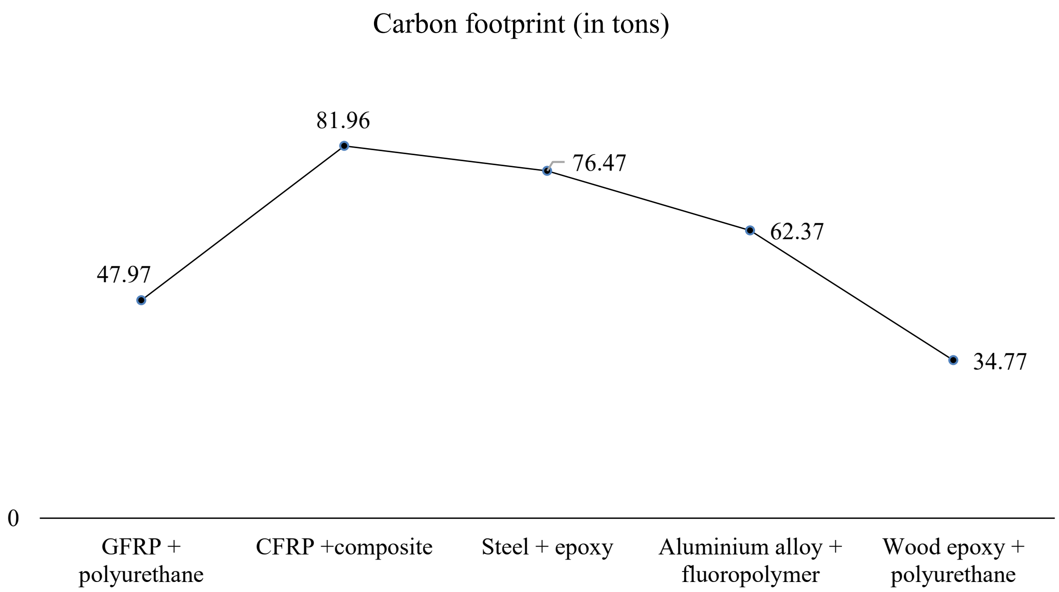

Figure 6. Carbon footprint analysis comparison.

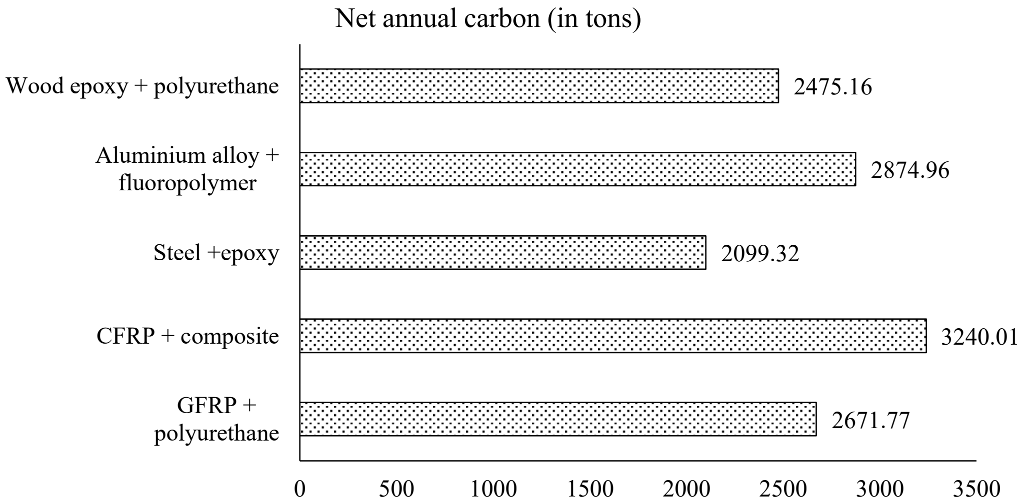

Figure 7. Net carbon analysis comparison.

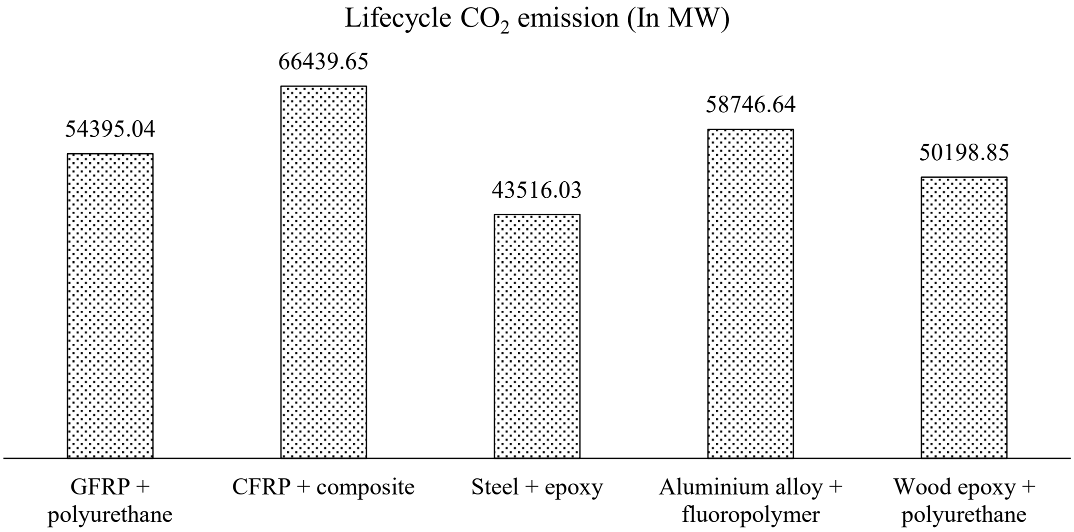

Figure 8. Lifecycle CO_2 emissions comparison.

Figure 7 shows the Net Annual Carbon Emissions (in tons) for selected wind turbine blade material combinations. This Figure gives important findings for their respective environmental performance. CFRP + composite is again the highest impactful combination for our environment due to its highest net annual carbon emissions while Steel + Epoxy offers as best sustainable combination. The significant gap between highest and lowest performer suggests a wide variance in carbon performance across materials.

When the lifecycle CO_2 emissions are compared for all combinations for average lifecycle of 20 years, it can be easily seen from Figure 8, that there is notable gap between CFRP + composite and the rest of material combinations and thus states that combination can be selected only at risk of high environmental cost. However this combination offers one of the best and advanced mechanical properties and performance, but it is the least sustainable choice due to its high lifecycle CO_2 emissions. From this comparison segment, Steel + Epoxy comes out to be the most sustainable material, having low emissions with advantageous costing. If consumer expects more balance between cost, performance and sustainability then Wood Epoxy + Polyurethane and GFRP + Polyurethane can be considered as good alternatives.

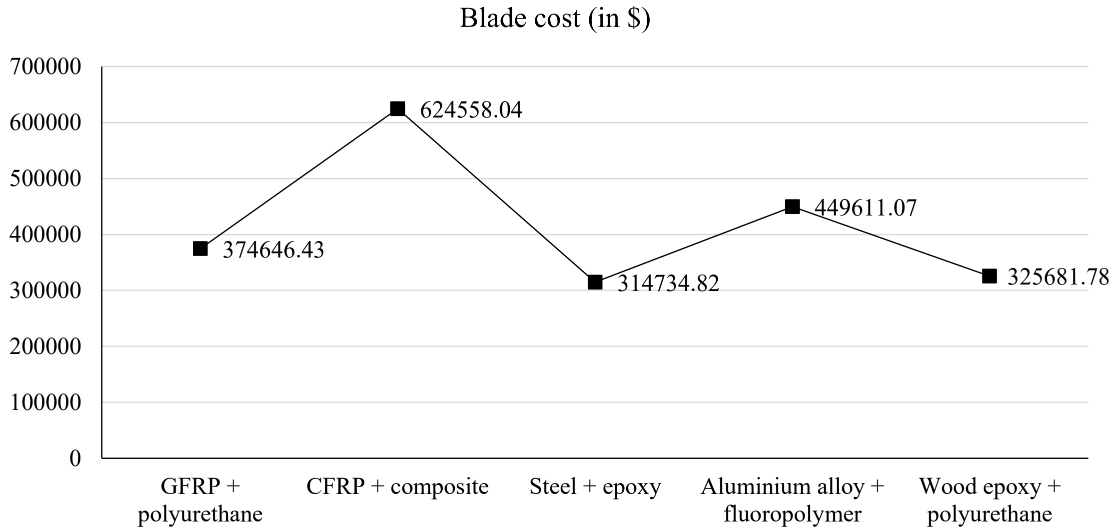

Figure 9. Cost analysis comparison.

Figure 9 illustrates the cost (in USD) analysis comparison for all five selected blade materials combinations. This analysis is utmost important for selecting required combination from variety of material combos. From this comparison, it is found that CFRP + Composite exhibits the highest cost while Steel + Epoxy is the most economical combination. The moderately priced combinations include GFRP + Polyurethane and Wood Epoxy + Polyurethane while Aluminum Alloy + Fluoropolymer comes in bit higher price range.

CONCLUSION AND FUTURE SCOPE

This study shows a trade-off between performance, cost and environmental impact of choosing wind turbine blade materials. Aluminium Alloy + Fluoropolymer, GFRP + Polyurethane is balanced and moderate in terms of power output and performance, whereas Steel + Epoxy can be used due to the low cost of the applications with limited budgets. The results emphasize the significance of a more comprehensive approach towards the choice of the materials, taking into consideration the operational and the environmental goals.

This paper can help in the design of effective, sustainable and cheaper wind energy solutions. The simulation study provides the detailed discussion of the performance, economic viability, and environmental performance of different wind turbines blade materials. The results indicate that under projects that are focused on the highest power production of 1.4 MW, CFRP + Composite to be used because of its high performance and best annual energy output of 4692 MWH. But with 3321 tons of annual CO_2 emissions makes it a doubtful choice of selection.

This leads to highest carbon footprints and more lifecycle emissions as compared to rest of combinations. Other materials that can be used in projects where efficiency and cost or environmental issues are considered are Aluminium Alloy + Fluoropolymer. The attention to the inadequate performance of Steel + Epoxy will make it more viable in wider contexts especially cost sensitive markets. Future studies may look into the use of hybrid materials or other coating to make the results more effective with minimal environmental concerns and focusing on uncertainty and sensitivity analysis.

Declaration of Interest

The author(s) declare(s) that there is no conflict of interest regarding thepublication of this manuscript.

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