Evaluation of environmental and economic impact of wind turbine blade manufacture at life-cycle level

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Abstract: Life cycle analysis is considered as a valuable decision-making tool to oversee the environmental impact of a product through its various stages. Starting from the raw material sourcing up to the end-of-life processes of the product. Life cycle costing is added to the life cycle analysis to augment the economic aspects. One of the main drawbacks of the life cycle analysis is the focus on single path for the life stages as it evaluates single option for each life stage and adds the impact to the following stages. this study presents a tool to evaluate the environmental and economic impact of different options in life cycle stages, determine the possible combination of different life cycle choices, and calculate the emissions, energy intensity and cost of each combination scenario. The study takes wind turbine blade as a case study, where glass fiber reinforced polymers and carbon fibers reinforced polymers are considered as a row material alternatives with two supply options Europe or China markets, four manufacturing site options (onsite, Denmark, Germany, and China) and four end of life processing options (reuse, pyrolysis, landfill, and mechanical grinding). The results range the different combinations scenarios emissions in the range of (74 – 17) tons of CO2 eq, the energy intensity between 261 GJ and 863 GJ, and the cost vary from 89000€ to 22,000€. This work presented a logical method for mapping, analyzing, and evaluating the environmental and economic sustainability of a wind turbine blade through different life cycle pathways.

Keywords: Life cycle analysis, life cycle cost, wind turbine, wind turbine blades, wind turbine blades end of life.

1. INTRODUCTION

Wind energy is considered one of the fastest growing renewable energies in Europe. Europe wind energy installed capacity increased from around 140 GW to 272 GW in 2023 (Costanzo et al., 2024). Sweden had even faster growth rate as it expanded from 5.1 GW to 16.3 GW in the same period (Swedish Wind Energy Association, 2024). Several studies proved high technical and economic potentials of wind energy in several areas of Sweden (Warners et al., 2023). In addition to the increased installed capacity, the wind turbines had also been scaled up to maximize wind energy exploitation. Between 2014 and 2023, Sweden's installed turbines count increased by less than half, while its installed capacity increased by more than three times (Swedish Wind Energy Association, 2024). This increase led to greater attention on wind energy sustainability with particular emphasis on the end-of-life treatment. Europe decommissioned 1.5 GW and repowered 736 MW of wind turbines in 2023 (Costanzo et al., 2024). Composite materials used to manufacture wind turbines blades and nacelles pose one of the main environmental challenges due to the difficulty of disposal and recyclability.

To better understand and manage sustainability, life cycle analysis and costing have been utilized as a valuable tool in this sector. Life cycle analysis (LCA) is a tool to evaluate the environmental impact of a product through its different life stages. The complete spectrum of stages starts from the initial raw material resources taken from the environment to the end-of-life disposal of the product (Bjørn et al., 2017). A general framework has been adopted to perform the LCA, this framework standardized through ISO 14040. The main steps in the standardized framework are goal definition, scope definition, inventory analysis and impact assessment. This logical approach permits to identify parts of the life cycle to emphasis, such as cradle to grave which cover the complete stages spectrum, and gate to gate which focuses on the manufacturing stage, starting from the raw material at the factory gate until the product leave the gate of the factory (Hauschild, 2017).

LCA has been used to evaluate energy sources environmental impact. for renewable energy, the focus is determining the emission reduction and evaluating the energy green pathways. Numerous LCA studies were conducted in wind energy with various goals. Most studies were for specific locations and farms sizes, due to the direct effect on impact per the generated power, mainly the impact of the transportation, installation, and operation and maintenance (O&M) stages. More recent studies focused on the environmental impact of the new technological development on wind turbines such as offshore installations (Brussa et al., 2023; Garcia-Teruel et al., 2022; Yuan et al., 2023). Some studies adopted comparative life cycle analysis (Schreiber et al., 2019). (Ozoemena et al., 2018) compared the environmental impact of 4 different technological improvements opportunities on a 114 MW onshore wind farm located in UK with 1.5 MW, the improvement opportunities evaluated were using stiffer carbon fiber to enlarge the rotor swept area without increasing the structural loads or equipment requirements, new tower concept using carbon fiber instead of metal allowing to increase the hub height from 65 meters to 100 meters without using higher cranes capacity, and permanent magnet generator using a lower rotational speed (150 rpm).

With expected increase in wind turbine capacities and installed numbers, wind turbine blades draw a significant interest in wind turbine LCA research area because of its high share on the total wind farm environmental impact (15-25) %, only exceeded by the tower (Mali and Garrett, 2022). In addition to the composite materials recycling challenges (glass and carbon fibers) which compromise around 80% of the total mass of the blade (Liu et al., 2019).

Considering the increased attention on carbon fibers and wind turbines blades LCA, this study introduces a scientific approach to evaluate and compare the environmental impact and cost of different options of three life cycle stages, taking a wind turbine blade as a case study.

2. METHODOLOGY

A case study has been made to describe the work done. The case study evaluates the alternative options of three stages of wind turbine life cycle namely (material acquisition stage, manufacturing stage and end of life treatment stage). The study blade is the National Renewable Energy Laboratory (NREL) WindPACT project reference turbine blade, 1.5 MW turbine with 33.35 m long and 4.335 tons in mass (Malcolm and Hansen, 2000). The case study assumes the turbine installation location near Eskilstuna Sweden. The study evaluates different options for each life cycle stage. The main evaluation criteria are the climate change impact represented by equivalent carbon dioxide emissions (kg CO2 eq), energy intensity in mega joules (MJ) and cost in Euros. Figure 1 shows the options evaluated.

2.1 Material Acquisition Stage

Materials considered are composite fibers and resin, as it compromises approximately 75% of the total blade weight (Bortolotti et al., 2019) . Recent studies proved that using carbon fibers as replacement of glass fibers is assumed to reduce weight due to the higher strength and stiffness. This study assumes a full replacement of glass fibers reinforced polymers (GFRP) by carbon fibers reinforced polymers (CFRP) with the assumption of 20% weight reduction based on (Corona et al., 2024) and (Ennis et al., 2019). Materials weight and cost are assumed based on (Bortolotti et al., 2019), environmental impacts are based on Environmental Footprint Database (Sala and Cerutti, 2018) used with OpenLCA software, (Jensen, 2019), (Rani et al., 2021) and (Stróżyk et al., 2024).

The fiber glass environmental impact is assumed to be the same regardless of the directions and axials of the fiber. Materials Prices taken from USA market assumed to be the same for Europe, and 20% less for China due to the low cost of labor and energy. The environmental impact of China sourced materials is scaled up based on the difference of energy mix impact between China and Europe. Material acquisition stage inputs are presented in Table 1.

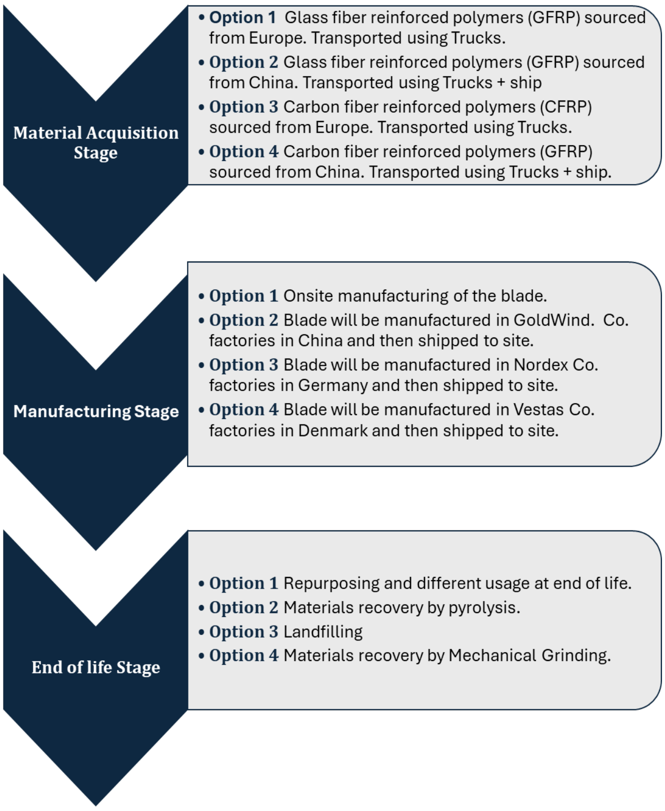

Fig. 1. Options per each stage.

Table 1. Material acquisition stage inputs

Description	Unit	Value
Glass fiber emissions	kg CO_2 eq/kg	4.79
Resin emissions	kg CO_2 eq/kg	6.59
Carbon fiber emissions	kg CO_2 eq/kg	11.2
Glass fiber energy intensity	MJ/kg	35.80
Resin energy intensity	MJ/kg	128.5
Carbon fiber energy intensity	MJ/kg	210
Glass fiber cost	€/kg	2.66
Resin cost	€/kg	3.38
Carbon fiber cost	€/kg	27.9
Fiber glass mass	kg	2453.79
Carbon fiber mass	kg	1963.03
Resin mass	kg	1292.16

2.2 Manufacturing Stage

Wind turbine blade manufacturing process involves various steps namely (material cutting, demold, infusion of the components, assembly, trim, overlay, posture, root cut and drill, root fastener installation, surface preparation, paint, surface finishing, weight and balance, inspection, and shipping preparation). These steps utilize simple equipment and machines in addition to a resin curing oven with a curing temperature approximately 70 ◦C. All equipment is assumed to be powered by electricity. Hence the main impact is caused by using electricity plus transporting the finished blade to the site. Manufacturing locations grid mix data are taken from Environmental Footprint Database (Sala and Cerutti, 2018) browsed using OpenLCA software. Manufacturing processes electricity demand and labor hours are based on (Bortolotti et al., 2019) . Electricity average price and labor cost are based on (ILOSTAT, 2022). Manufacturing stage inputs are shown in Table 2.

2.3 End of life Stage

To improve wind power sustainability multiple academic and industrial parties are investigating several end-of-life options for wind turbine blades. The studies vary from adding secondary life to the wind turbine blade and using them as a construction material up to numerous ways to recover the fibers (Paulsen and Enevoldsen, 2021) (Rani et al., 2021) (Yousef et al., 2024). Main proposed options for the end-of-life stage are summarized below:

- Functional repurposing (cutting the wind turbine in pieces and using them for simple structures like bus stops and barns).
- Mechanical grinding (producing fiber rich powder to be used for new fibers production).
- Pyrolysis (obtaining pyrolysis gas and oil with other solid by products).
- Fluidized bed (reclaiming fibers through burning out the resin).
- Solvolysis (chemically decomposing the fibers matrix to get the fibers).
- High voltage pulse fragmentation (decomposing the fibers matrix by high voltage electrolysis process).
- Mechanical shredding and cement or asphalt co processing.

This study assumes four options for end-of-life stage, which are:

- Repurposing blade as a high voltage transmission pole based on (Henao et al., 2024).
- Fibers treatment through pyrolysis.
- Recovering fibers through mechanical grinding.
- Land filling at farm stie.

The inputs data for the end-of-life stage shown in Table 3 are taken from (Paulsen and Enevoldsen, 2021; Jensen, 2019; Liu et al., 2019; Sproul et al., 2023). The negative impact values represent the net gain acquired through the end-of-life treatment, it presents the difference between the recycled or reused fibers and the production of virgin fibers or construction materials.

Table 2. Manufacturing stage inputs

Description	Unit	Value
Sweden electricity grid mix emissions	kg CO_2 eq/MW	0.0834
Denmark electricity grid mix emissions	kg CO_2 eq/MW	0.60768
Germany electricity grid mix emissions	kg CO_2 eq/MW	1.19462
China electricity grid mix emissions	kg CO_2 eq/MW	1.9158
Sweden electricity grid mix energy	MJ /MW	3.80815
Denmark electricity grid mix energy	MJ /MW	3.8283
Germany electricity grid mix energy	MJ /MW	7.57788
China electricity grid mix energy	MJ /MW	9.54177
Sweden electricity grid mix average price	€/MW	265.05
Denmark electricity grid mix average price	€/MW	325.5
Germany electricity grid mix average price	€/MW	372
China electricity grid mix average price	€/MW	74.4
One blade manufacturing labor hour	h	407.37
One blade manufacturing electric energy in MW	MW	1.5725
Labor cost in Sweden	€/h	47.8299
Labor cost in Denmark	€/h	53.3448
Labor cost in Germany	€/h	46.0908
Labor cost in China	€/h	4.464

2.4 Transportation and shipping

Transportation is considered for materials and manufactured blades. Land transportation is assumed to be by 7 Ton trucks for the materials and 30-ton trucks for the blade. A full 30 Ton truck is assumed for blade transportation, as it depends on the size required to fit the blade rather than the weight dependency. The China options sea transportation assume container shipping for materials and medium barge for blade. Distances assumed are 1000 km for material transportation in Europe and Google maps factory to site measured distance for the blade.

No road topology is considered in the study, the study assumes all roads are paved. Transportation main inputs are shown in Table 4. Emissions and energy intensity are based on Environmental Footprint Database (Sala and Cerutti, 2018) browsed by OpenLCA software, transportation cost figures are based on (Sander van der Meulen et al., 2023).

Table 3. End of life stage inputs.

Description	Unit	Value
Repurposing emissions	kg CO_2 eq/kg	-1.2
Pyrolysis emissions	kg CO_2 eq/kg	-2.06
Landfill emission	kg CO_2 eq/kg	0.05477
Mechanical grinding emissions	kg CO_2 eq/kg	-1.29
Repurposing energy	MJ/kg	1.351
Pyrolysis energy	MJ/kg	30
Landfill energy	MJ/kg	0.35827
Mechanical grinding	MJ/kg	4.8
Repurposing Cost	€/kg	0
Pyrolysis Cost	€/kg	0.2556
Landfill Cost	€/kg	0.0882
Mechanical grinding	€/kg	0.0856

2.5 Model and calculations

To evaluate the options of each stage and calculate the total emissions, energy intensity and cost of the three stages, a python model is built to determine all scenarios of options combinations and calculate the total impacts and cost. Figure 2 demonstrates the model schematic diagram.

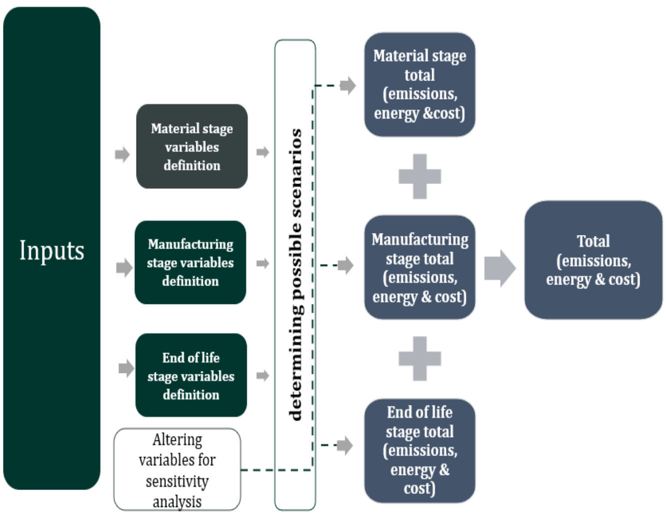

Fig. 2. Model structure.

Sensitivity analysis is made to explain the effect of (carbon fiber mass, glass fiber mass, materials transportation distance, manufacturing location distance to site, manufacturing location grid mix, manufacturing location electricity price, manufacturing location labor cost, recycling method emissions, recycling method required energy and recycling method cost). The sensitivity analysis baseline scenario is GFRP as a material sourced from Europe, Germany as blade manufacturing location, and repurposing as an end-of-life treatment. The emissions and energy intensity of electricity are treated as independent variables, disregarding their mutual dependency due to the complexity of their relationship and reliance on electricity generation and grid operation technologies.

The study is conducted under the limitation of the data found in literature and Environmental Footprint Database, Industrial sources found was only for complete turbines, and the data source they use for LCA inventory was commercial databases. No consideration is made for the time value of money as the main future cost element is the end-of-life cost which is sourced based on literature estimation as most of the composite materials recycling methods are not mature enough yet.

Table 4. Transportation inputs

Description	Unit	Value
7-ton truck emissions	kg CO_2 eq/ton.km	0.2912
7-ton truck energy	MJ/ton.km	1.94286
7-ton truck cost	€/Ton.km	0.125
Containers ship emissions	kg CO_2 eq/ton.km	0.02954
Containers ship energy	MJ/ton.km	0.18034
Containers ship cost (€/Ton.km)	€/ton.km	0.0014
Site distance	km	0
Vestas factory distance to farm location	km	770
Nordx factory distance to farm location	km	930
Goldwind factory distance to farm location	km	900
China- Europe Sea distance	km	23000
Blade truck emissions	kg CO_2 eq/km	2.79529 9
Blade truck energy	MJ/km	18.6991 4
Blade cost	€/km	9.7565
Blade Barge emissions	kg CO_2 eq/ton.km	0.16447
Blade Barge energy	MJ/ton.km	1.04824 6
Blade Barge cost	€/Ton.km	0.09103 5

3. RESULTS AND DISCUSSION

Determining all combinations of options result in 64 possible scenarios combining one option for each stage. Figure 3 presents the total climate change impact, energy intensity and cost of the resulting 64 scenarios.

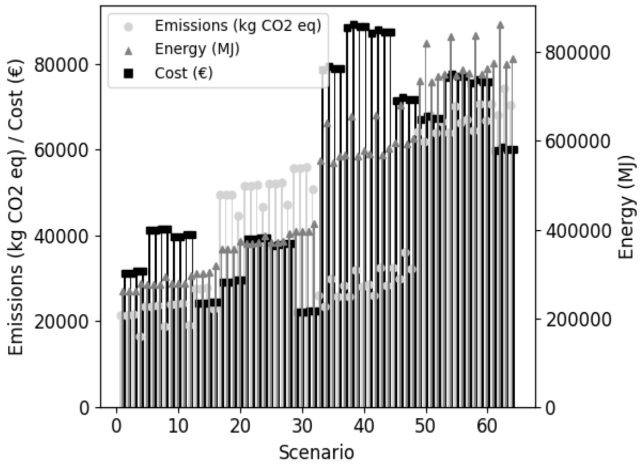

Fig. 3. Emissions, energy intensity and cost per scenario.

The total emissions vary between (16,525 to 74,384) kg CO2 eq. The lowest emissions come with scenario 4, which represents GFRP as a material sourced from Europe with onsite blade manufacturing and mechanical grinding as a recycling option. The highest value represents CFRP as blade material, with China as material source and manufacturing location in addition to landfilling as end-of-life option.

Total energy intensity calculations fell in the range of (261,179 – 862,661 MJ). The highest energy intensity score is for scenario number 62 which represent a CFRP blade with China as material source and blade manufacturing location, and pyrolysis as end-of-life option. The lowest is for the GFRP blade with material sourced from Europe and site as a blade manufacturing location with repurposing as end-of-life option.

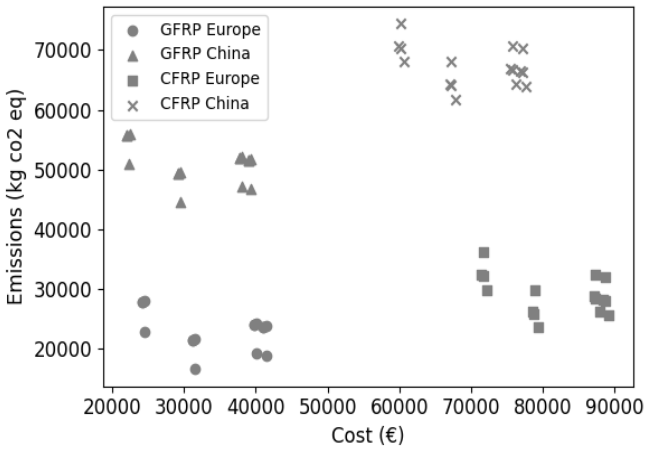

Fig. 4. Scenarios cost versus emissions.

Figure 3 shows that CFRP sourced from Europe with Denmark as a manufacturing location and pyrolysis as end-of-life option involve the highest cost blade (89,159 €), while the lowest cost (22,115 €) represents a GFRP blade with material source and blade manufacturing location in China and repurposing as an end-of-life option.

The results show variation among the different scenarios with a general trend of high emissions and energy intensity for the CFRP blade where China set as material source, while excessive cost follows the carbon fiber sourced from Europe and blade manufactured in Europe. The high effect of location can be seen on all indicators, this can be attributed to the effect of transportation distance and type, and the effect of the energy mix in each location. The high energy demand, emissions and cost related to carbon fiber manufacturing made it less favorable compared to glass fiber.

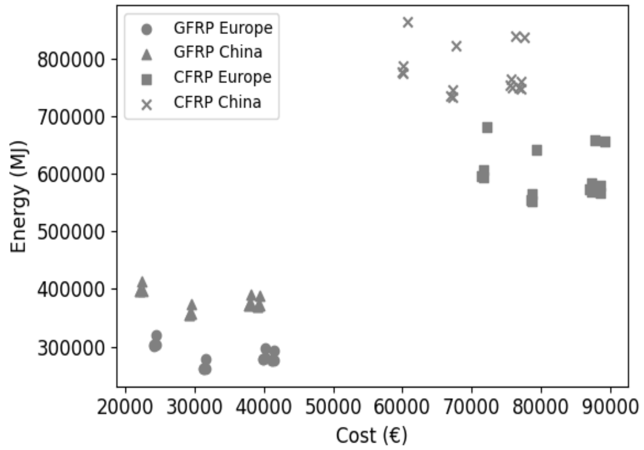

Fig. 5. Scenarios cost versus energy intensity.

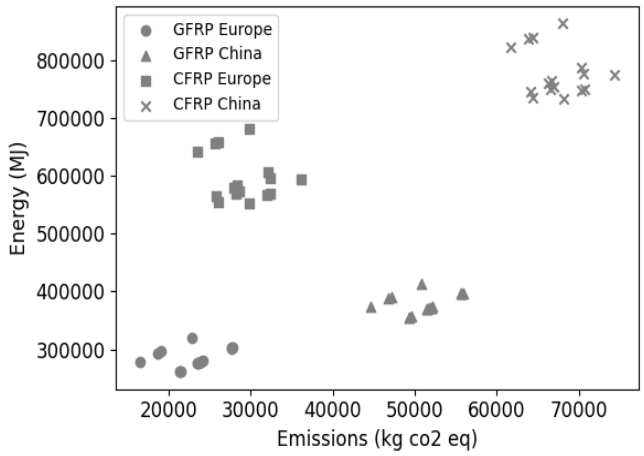

Fig. 6. Scenarios emissions versus energy intensity.

Correlation can be seen between the low cost and low emissions for the scenarios including European sourced GFRP and China as a blade manufacturing location, this can be attributed to the tradeoffs between the low emissions related to the glass fibers manufacturing in Europe and the low cost of labor and electricity in China. As the blade manufacturing processes requires small amount of power (1.57 MW) the effect of high emissions of China grid mix is not significantly affecting the results in this case (Fig. 4).

Correlation between low cost and low energy can be seen for the scenarios including GFRP as material, regardless of the manufacturing location or end of life treatment method, this result driven by the high energy intensity and inflated cost of the CFRP compared to the GFRP (Fig. 5).

Energy intensity and cost relations show higher sensitivity to the material source in the case of CFRP more than for GFRP case (Fig. 5). Europe CFRP represent the high-cost medium energy intensity and China CFRP represent the high energy intensity and medium cost. The high cost and high energy intensity comes with the scenarios linking carbon fiber and Europe manufacturing locations resulting from the high energy intensity of the carbon fibers and the high cost of labor in Europe.

reduce approximately 20% of the fiber glass emissions. The same applies for energy intensity which is affected mostly by the recycling method but with significantly minimal impact compared to the emissions. Most of the recycling methods require energy to perform the recycling and to produce the recovered materials. In addition to the recycling method, we can see the effect of changing the mass of carbon fiber and glass fiber affecting the energy intensity by 1.036 this effect is due to the high energy intensity of the carbon fibers compared to the glass fibers and the equivalent numbers caused by the interchangeability between the two materials as we reduce the glass fibers, we increase the carbon fibers and vice versa.

The minimal sensitivity of the emissions, energy intensity and cost for most variables with consideration of the wide range of

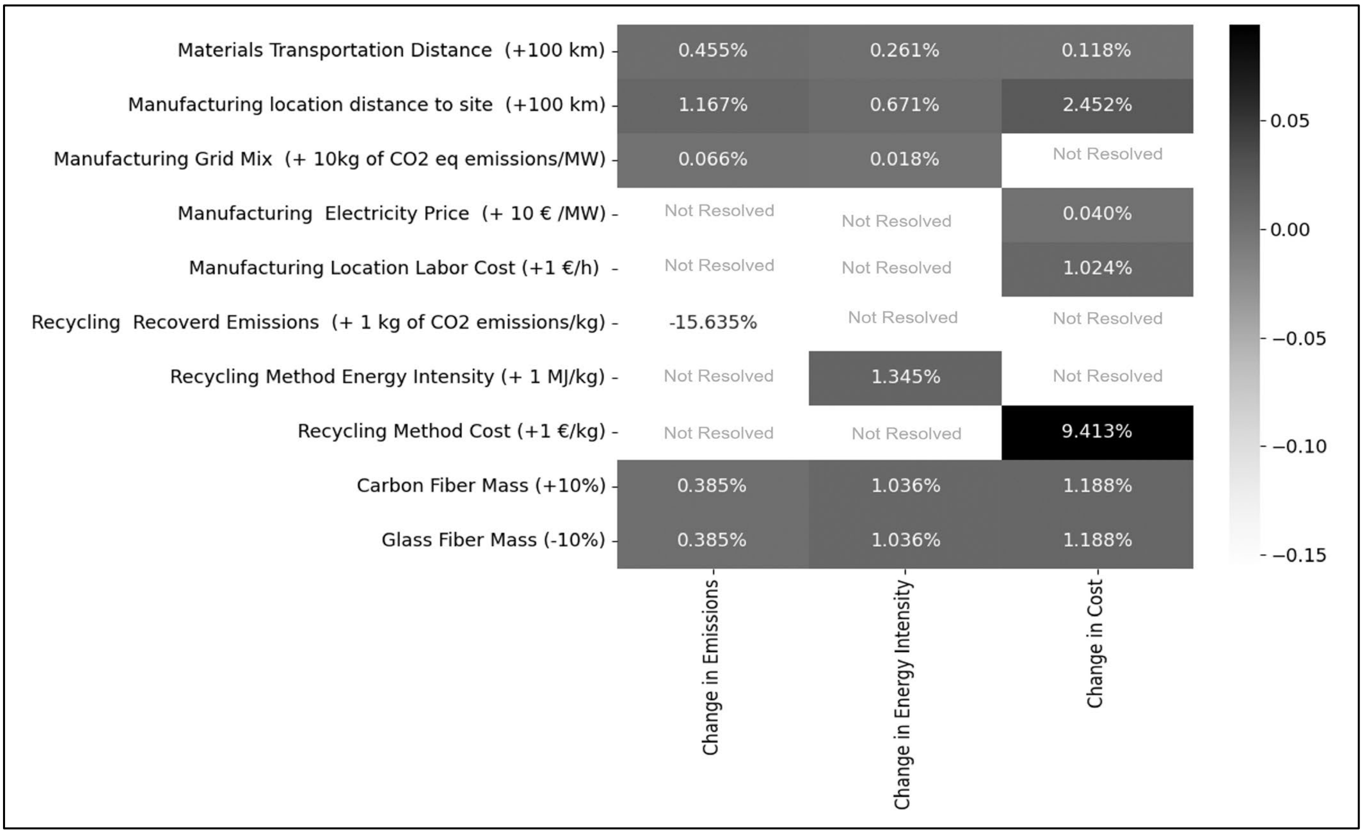

Fig. 7. Emissions, energy intensity and cost sensitivity to variables change.

Figure 6 presents the relation between the emissions and energy intensity of the scenarios. The effect of grid energy mix can be seen in the difference between Europe and China as a materials sources and manufacturing location. The GFRP of European source represent the lowest emissions and energy intensity, while the CFRP of the same origin imposed higher emissions and energy intensity compared to China sourced GFRP but lower emissions and energy compered to Chinese sourced CFRP.

Figure 7 represents the sensitivity analysis results, showing the percentage change in emissions, energy intensity and cost as result of changing one of the variables. Emissions exhibits high sensitivity to the end-of-life treatment method. This can be justified by the high materials emissions per weight compared to the other stages, recovery of 1 kg CO2 eq /kg

the scenarios results prove the significance of joint effect of changing multiple variables at the same time as each scenario present a unique set of variables values.

Changes in electricity price, labor cost and recycling method cost only affect the total cost as no relation applied between the cost and the other impacts.

4. CONCLUSION

The work presented has demonstrated a logical approach to evaluate several life stage options, which can improve the LCA studies. Furthermore, it has highlighted the importance of composite materials recycling. The study results have proved the magnitude of joint effect of changing several variables on the LCA and LCC studies.

The study results have shown the lowest climate change impact for scenarios 4 (16525 kg CO2 eq), lowest energy intensity for scenario 1 (261179 MJ), and lowest cost for scenario 29 (22,115 €), while the highest impacts have been the results of scenario 63 (74,384 kg CO2 eq), scenario 62 (862,661 MJ), and scenario 38 (89,159 €). This has proven that no single scenario can give the lowest or highest impact in all categories and gives room for optimization problem solution.

This work can be a valuable initial step in studying wind turbine blades material sourcing, manufacturing, and recycling.

Future work needs to include more life cycle stages, extra investigation on the interdependency of variables like the electricity mix relation with cost, and modeling different transportations mode and topography.

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