detritus | Multidisciplinary Journal for Circular Economy and Sustainable Management of Residues

CISA

ENVIRONMENTAL ASSESSMENT OF GLASS FIBER REHINFORCED POLYMER (GFRP) VALORISATION PROCESSES FROM THE DECOMMISSIONING OF WIND TURBINES

Emanuela De Marco *, Valentina Fantin, Laura Cutaia and Cristian Chiavetta

Department for Sustainability, Energy and Sustainable Economic Development, Italian National Agency for New Technologies, ENEA, Italy

Article Info:
Received:
27 June 2024
Revised:
30 August 2024
Accepted:
4 September 2024
Available online:
25 October 2024

Keywords:
Life cycle analysis
Glass fiber reinforced polymer
Recycling
Wind turbine blades

ABSTRACT

The production of wind energy is one of the most mature technologies in the field of renewable energy, and the rapid technological advances bring out the need to replace the old models of wind turbines with more efficient versions. Operators must plan the management of a large amount of resource flows from the end-of-life wind farm disposal. The use of composite materials, in particular epoxy resins reinforced with glass fibers (Glass Fiber Reinforced Polymer - GRFP), most used in the wind blades, makes the material separation and recovery operations quite complex. The purpose of the study is to compare the environmental performance of the life cycle of two treatment processes (mechanical recycling and co-processing in cement kiln), identified by literature as possible technologies for the treatment of GFRP, including also the environmental benefits obtainable through the valorisation of both the waste material itself (used as fuel) and the secondary material obtained at the end of the treatment process. The LCA study provides some general considerations about the possible recycling and recovery of GFRP material contained in wind turbine blades. In general terms, it can be stated that co-processing in cement kilns is a highly efficient process because it allows energy to be recovered from the waste material and part of it to be integrated into the clinker production process.

1. INTRODUCTION

Since wind energy is one of the most promising sources of renewable energy and that the installation of wind plants has grown exponentially in recent years (IEA, 2023), it is essential to address the economic and environmental issues of the management and end-of-life treatment of composite waste (glass or carbon fibre reinforced polymers) resulting from the decommissioning of wind power plants and, in particular, from wind turbine blades. Currently, 2.5 million tons of composite material are in used in the wind energy industry globally and it is estimated that by the end of 2023 about 14,000 blades could be decommissioned, corresponding to 40,000-60,000 tonnes (WindEurope - Cefic - EuCIA, 2020).

However, so far, the amount of composite waste generated by wind turbines accounts for only 10% of total thermoset composite waste (WindEurope - Cefic - EuCIA, 2020). Since these volumes are relatively low, a recycling activity with only this waste stream is rather difficult and expensive from both a technological and economic point of view. Moreover, from a normative point of view, national and European norms are currently limited and not uniform in the regulation of the end-of-life of composite materials. In general, these have the objective of limiting the disposal of composite materials in landfills.

Nevertheless, different techniques of recycling composite materials are currently available, but only some of them are applied at industrial scale, due to their different technology readiness, high investment and operating costs (Wind Europe, 2020). Composite materials, consisting of epoxy resins reinforced with carbon fibers (CFRP - Carbon Fiber Reinforced Polymer) or, most commonly used in wind turbines, with glass fibers (GFRP - Glass Fiber Reinforced Polymer) can be recycled or recovered by mechanical grinding, thermal (pyrolysis, fluidized bed), thermochemical (solvolysis) or electrochemical (high voltage fragmentation) processes or by a combination of them.

The aim of this study is to assess and compare, through the standardised Life Cycle Assessment method (ISO 2021a, ISO 2021b), the environmental impacts of the life cycle of two GFRP waste material treatment processes resulting from the decommissioning of wind turbines. The LCA studies and their results are presented in the following paragraphs.

* Corresponding author:
Emanuela De Marco
email: emanuela.demarco@enea.it

Detritus / Volume 29 - 2024 / pages 63-73
https://doi.org/10.31025/2611-4135/2024.19437

2. MATERIALS AND METHODS

2.1 Goal and scope of the study

2.1.1 Goal of the study

The LCA method was applied to the following end-of-life treatment processes for GFRP waste, in order to evaluate and compare their environmental performances:

- Mechanical recycling (Scenario 1);
- Co-processing (also known as "the cement kiln route"), which is used for recycling GFRP waste because it is technologically and economically more advantageous than mechanical recycling (Gonçalves et al., 2022) (Krauklis et al., 2021) (Scenario 2). This technology is already used on a commercial scale because it is considered, at the moment, one of the most solid options for the end-of-life management of wind turbines since it provides several advantages:
  - Reduction of the amount of fossil fuel (coal) used in the clinker production process;
  - Reduction of both the use of raw material (sand) and the emissions of its production to provide silica to the kiln, because silica is replaced by glass fibres contained in the input composite material;
  - No residue generated, because the mineral content in the composite material is incorporated into clinker.

For both technologies the environmental benefits from the GFRP waste valorization as fuel and/or as secondary material from the treatment process have been considered.

An attributional approach was used for the study, reproducing the existing supply chain and using background processes representative of the average market consumption mix (European Commission - Joint Research Centre, 2010).

2.1.2 Function of the system, functional unit and reference flow

The function of the system is the management and treatment of GFRP waste material resulting from the disposal of a wind farm located in Italy which consists of 6 wind turbines at the end of their useful life.

The functional unit is 1 MW of power, and the reference flow is the amount of waste material GFRP collected from the disposal of the 6 wind turbines needed to obtain 1 MW of power.

2.1.3 Description of the recycling processes

Most of the wind turbine blades on the market are made of GFRP. However, there are other blade types partially (hybrid) or totally made of Carbon Fiber Reinforced Polymer (CFTP). This study considers wind turbine blades are consisting only of GFRP. In this case, the two main materials of the blades are glass fiber and polymer resin. Other support components, made of metal materials and lower than 5% in weight in most of the wind turbine design were not considered in the study because it was assumed that they are removed during the first phase of dismantling (Liu et al., 2022).

In the wind turbine model analyzed in the study, the GFRP material is contained in the blades, the nose cone and the housing of the nacelle; the amount of GFRP contained in a turbine is about 13 tons (Vestas, Wind Systems, 2024).

The LCA study considered two of the commonly used, due to their technological and economic advantages and high maturity level, end-of-life treatment technologies for GFRP waste material resulting from the decommissioning of wind turbines (Gonçalves et al., 2022) (Krauklis et al., 2021):

- Mechanical Recycling: this process involves a first phase of material dimensional reduction by fragmentation and grinding, and any subsequent sifting to separate and classify the crushed material in different sizes. The machines used to dimensionally reduce the material can be different: the hammer mill can better process the waste material and obtain a ready-to-use material for new composites. The material obtained at the end of the recycling process has the form of granules (rich in glass fibers) or powders (rich in polymer resin) and can be used as a filler in the building industry or as a reinforcement in new composite products (Gonçalves et al., 2022) (Oliveux et al., 2015). The characteristics of the obtained material largely depend on the type of input material and the grinding technique used. In general, its value is poorly competitive if compared to virgin materials. Moreover, only a part of the recycled product is suitable to be used for the production of new composites and in some cases further processing (i.e., grinding and screening) have to be added for a better usability, in other applications. When used as a filler, an average particle size lower than 10 μm is required. In this case, the larger particles will have to be ground again. Materials leaving the recycling process can be generally classified into two categories (Palmer, 2009):
  - "Coarse" quality materials consisting of larger particles, typically bundles of glass fibers held together by the resin: they are too large to be used as filling materials but can be used as reinforcement in new composites or can be broken into smaller pieces;
  - "Fine" quality materials, ground into very fine particles, to be used as fillers.
- Co-processing in a cement kiln (Jacob, 2011) (Krauklis et al., 2021) (Yazdanbakhsh et al., 2014): as a result of the dismantling of the rotor, the blades are transported to the co-processing, which consists of a furnace for the production of clinker, the constituent material of cement. The process uses the polymer matrix of the waste material GFRP as fuel in the process itself (thus replacing the coal normally used in the combustion process), while the inert fibrous component of GFRP, based on alumina borosilicate, constitutes the mineral raw material that can be used to produce clinker (the basic component, made from clay and limestone, for cement production). It can therefore be considered that the process uses 100% of the input GFRP waste material (even if a part of it it's just energetically valorized), because the whole waste material is used for energy recovery, since it is a fuel for combustion in the furnace,

or for material recovery, because the the secondary material leaving the furnace can be used for a subsequent valorisation.

2.1.4 System boundaries

The system boundaries are "from gate to grave", including only the phases of GFRP waste material transport from the wind farm to the treatment plant and the waste treatment with mechanical recycling or co-processing in a cement kiln.

Since both treatment process leads to a multifunctionality, a system expansion approach was used, similarly to Karuppannan Gopalraj et al., (2021) and according to ISO 14040-44, in order to include the additional function of the analyzed systems. In this way, the substitution of coal (as fuel for combustion) and inert material (sand) for clinker production was considered by modeling specific avoided impacts (Figure 1). According to Karuppannan Gopalraj et al. (2021), a "zero burden" approach was applied for GFRP waste material, which did not have any environmental impact due to its production. Therefore, the LCA study does not consider the environmental impacts due to the waste production phases (which are equal in Scenarios 1 and 2), because the purpose of the study is to compare the environmental performances of the two different systems for recycling and recovery the GFRP waste material.

2.1.5 Data quality and Life Cycle Impact Assessment method

For the LCA study, secondary data from different literature sources and related to the specific treatment processes for the management of GFRP waste material were used, the specific characteristics of the GFRP material itself and the technical characteristics of the secondary material obtained were used. More details about the used literature sources are included in the Inventory paragraph.

The study was carried out using SimaPro 9.5 software and Ecoinvent 3.9.1 database (Wernet et al., 2016) for the modeling of background data. From the geographical, time and technological representativeness point of view, the more recent data about European or global average technologies available in Ecoinvent 3.9.1 were used.

The impact assessment method used is EF 3.1 (Zampori et al., 2019), applying only the phases of characterization and normalization, as they are considered more scientifically robust. In regards to the geographical, temporal and technological representativeness of the background data used, reference was made to European average technologies when available, otherwise global, and, as last option, to the data available in Ecoinvent 3.9.1 (Wernet et al., 2016).

2.2 Inventory analysis

For both scenarios, the total amount of GFRP waste material contained in the wind turbines, rotor cone nose and nacelle housing were considered equal to 12,838.62 kg (amount referred to 1 MW of power of the entire wind farm).

In both scenarios an average road transport distance (by a Euro 6 truck with an average load capacity of 32 tonnes) of 200 km was considered from the wind farm to the treatment plants (Karuppannan Gopalraj et al., 2021).

In addition, an alternative distance (AD) of 400 km from the plant to the treatment site was considered for both scenarios in order to assess the impact of transport on the two processes. Furthermore, for the co-processing scenario (Scenario 2), an alternative option has been studied where the transport of the material over the 400 km distance is carried out by vehicles with a lower capacity (a Euro 6 lorry with an average load capacity of 5.7 tonnes), on the assumption that the crushing phase of the material takes place at the dismantling site (Option A).

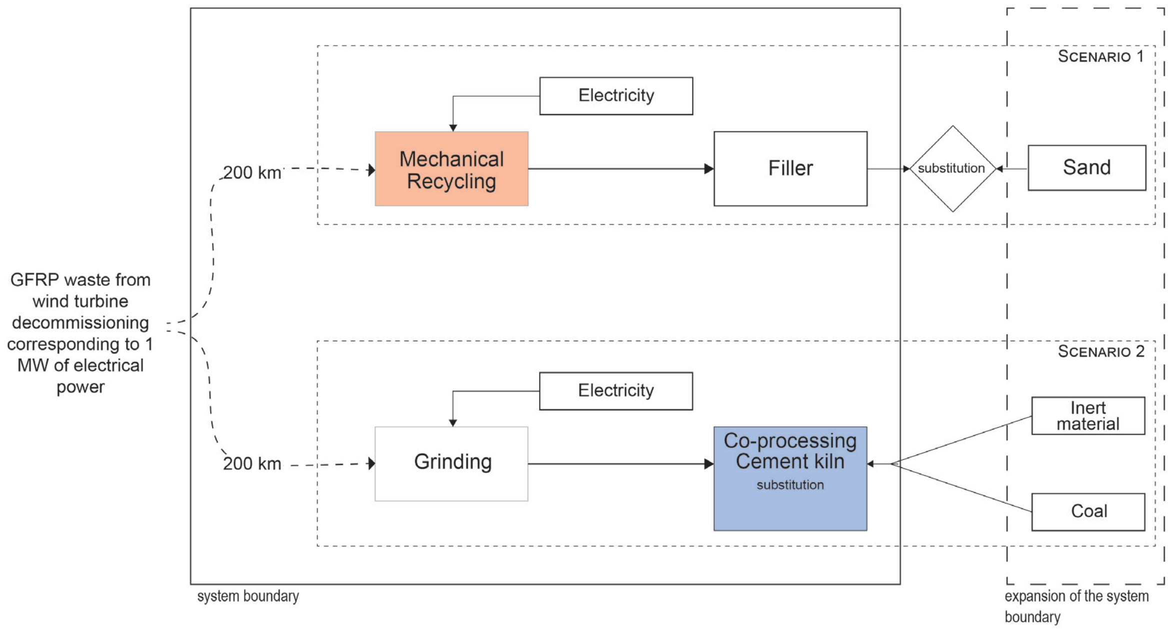

FIGURE 1: System boundary.

This option was considered because roads may not be suitable for large vehicle transport and it may be necessary to reduce the size of the material before it is transported to the cement plant so that it can be handled by smaller vehicles.

In Scenario 1 (mechanical recycling), the energy consumption for the mechanical treatment of GFRP waste, i.e.to cut the blades of the dismantled blades into pieces, to chop and grind the waste material into powder and into fiber sections of about 10 mm was considered. According to Kurapannan Gopalraj (2021), energy consumption for this process was assumed to be electricity, using the Italian medium voltage mix and equal to 0,27 MJ/kg of treated GFRP waste material, in agreement with Liu et al. (2019) and Howarth et al. (2014),

To calculate the amount of exploitable secondary material, the GFRP waste material was considered to consist of the following components (Jacob, 2011):

- 67% in weight was assumed to be a mineral part made of fiberglass, rich in mineral components such as silica, calcium carbonate, alumina;
- 33% in weight was assumed to be an organic polymer part.

In order to quantify the benefits deriving from the use of the secondary material obtained at the end of the mechanical treatment (recycled material), in agreement with Liu et al. (2019), it was assumed that this benefit is proportional to the tensile strength of the fibrous component of the GFRP waste material, because tensile strength is one of the most important properties of wind turbine materials.

In detail, it was considered that the fibrous component of the secondary material has a tensile strength of 78% of the tensile strength of the fibrous component of virgin GFRP material (Liu et al., 2019) and that the yield rate of the fibrous component at the end of the mechanical recycling process is equal to 55% (Liu et al., 2019) (Palmer, 2009); similarly, it was considered that the polymer component of the secondary material has a technical performance equal to 50% of the performance of the polymer component of the virgin GFRP material and that the yield rate of the polymer component at the end of mechanical recycling is 100% (Liu et al., 2019).

Table 1 summarizes the data and parameters used in Scenario 1 for mechanical recycling. By multiplying these parameters and yield rates by the quantities of the fibrous component and polymer component of the GFRP waste material, the quantities of recycled fibre and recycled polymer released from the mechanical treatment were finally calculated. These quantities were then added together to obtain the total amount of secondary material obtained, assuming that it is not further separated and constitutes a homogeneous mix of fibrous and polymer components.

In order to identify the product replaced by the secondary material stemming from the mechanical recycling

TABLE 1: Inventory data and parameters used for modelling mechanical recycling and co-processing processes in cement kilns.

Process	Data/parameter	Unit	Values Scenario 1	Values Scenario 2	Reference
Mechanical recycling (scenario 1)					
	Total amount of GFRP waste material contained in wind turbines, rotor cone nose and nacelle housing, referring to 1 MW of the entire wind farm	kg	12,838.62		Authors calculation based on Vestas data (2015)
	Energy consumption for mechanical treatment, with reference to 1 kg of treated GFRP material	MJ/kg	0.27	-	Howarth et al. (2014); Liu et al. (2019)
	Tensile strength of the fibrous component of the secondary material compared to the tensile strength of the fibrous component of the virgin GFRP material	%	78	-	Liu et al. (2019); Liu et al. (2022)
	Final yield rate of fibrous component of GFRP waste material	%	55	-	Liu et al. (2019); Palmer (2009)
	Technical performance of the polymer component of the secondary material, compared to the technical performance of the polymer component of the virgin GFRP material	%	50	-	Liu at al. (2019)
	Final rate of return of polymer component of GFRP waste material	%	100	-	Liu et al. (2019); Keith et al. (2017)
	Distance from wind farm to treatment plant	km	200	-	Karuppannan Gopalraj et al. (2021)
	Alternative distance (AD) from wind farm to treatment plant	km	400	-	Authors calculation
Co-processing in cement kiln (scenario 2)					
	Total amount of GFRP waste material contained in wind turbines, rotor cone nose and nacelle housing, referring to 1 MW of the entire wind farm	kg		12,838.62	Authors calculation based on Vestas data (2015)
	Energy consumption for grinding pre-treatment, referring to 1 kg of treated GFRP material	MJ		0.27	Howarth et al. (2014) Liu et al. (2019)
	Superior calorific value of GFRP waste material	MJ/kg	-	33.5	Karuppannan Gopalraj et al. (2021)
	Higher calorific value of coal	MJ/kg	-	28	Karuppannan Gopalraj et al. (2021)
	Distance from wind farm to treatment plant	km	-	200	Karuppannan Gopalraj et al. (2021)
	Alternative distance (AD) from wind farm to treatment plant	km	-	400	Authors calculation

of the waste material GFRP (avoided product), several papers on its possible uses were analysed. The approach of Yazdanbakhsh et al. (2014) was followed: according to the authors, mechanically recycled GFRP waste has a potential application as a filler in Portland cement mortar and concrete.

Further possible uses of the recycled material include:

- its transformation into a compound, made of ground GFRP (obtained from mechanical recycling), mixed with virgin or recycled plastic resins (polypropylene, polyethylene, acrylonitrile butadiene styrene) for injection moulding (Gees Recycling, 2024);
- the production of recycled fibreglass panels made of recycled fibre-reinforced composites (glass fibre, kevlar, carbon fibre, etc.) that are finely ground and re-glued at high pressure with minimum percentages of adhesives (3D Wall Panels Italia, 2024).

Nevertheless, in the LCA study these uses could not be accounted for, due to the lack of appropriate datasets in the Ecoinvent database, which are necessary to identify and model the replaced material. The study therefore assumed that the substituted product is sand, used as a filler, using a suitable Ecoinvent dataset to model its production, considered an avoided impact. Finally, the amount of replaced sand was considered to be equal to the total amount of secondary material obtained at the end of the recycling process, calculated as specified in the previous paragraph. Table 2 shows the input and output data used to model Scenario 1, and the Ecoinvent datasets used.

As regards the co-processing in a cement kiln (Scenario 2), GFRP material waste is first ground to reduce its size, and then fed into the kiln where combustion takes place: the polymer organic component (33% of the total amount of GFRP waste material) burns, providing energy, and the mineral fiber component (67% of the total amount of GFRP waste material) (Jacob, 2011), can be used as the main component of Portland cement, providing the raw material for the production of cement clinker (Yazdanbakhsh et al., 2014).

The study therefore accounted for the electricity consumption to grind GFRP waste material before it is inserted into the furnace. Similarly to mechanical recycling, it was assumed that this electrical consumption, modeled through the use of the Italian medium voltage electric mix, was equal to 0.27 MJ/kg of treated waste (Liu et al., 2019), because the grinding process is conceptually the same, from the technological point of view, to the grinding of mechanical recycling. Karupannan Gopalraj et al. (2021) has a value of 0.09 MJ/kg of treated waste for grinding that takes place before being placed in the oven. However, in this study a conservative approach was used, adopting the same energy consumption of mechanical recycling.

Moreover, it was considered that the polymer organic component of the GFRP waste material, because it is a fuel, is used to replace fossil fuels for the combustion process inside the furnace (energy recovery), thus avoiding

TABLE 2: Mechanical recycling and Co-processing in cement kiln input and output data, referring to 1 MW of power of the entire wind farm.

	Unit	Values	Dataset used by Ecoinvent
Mechanical recycling (scenario 1)			
Input			
Energy for grinding	MJ	3,466.43	Electricity, medium voltage {IT}| market for electricity, medium voltage | Cut-off, U
Distance from wind farm to treatment plant (200 km)	kg*km	2,567,723.08	Transport, freight, lorry >32 metric ton, EURO6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Cut-off, U
Alternative distance (AD) from wind farm to treatment plant (400 km)	kg*km	5,135,446.154	Transport, freight, lorry >32 metric ton, EURO6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Cut-off, U
Output			
Power of the entire wind farm	MW	1	
Replaced inert material (sand)*	kg	5,808.57	Sand {RoW}| market for sand | Cut-off, U
Co-processing in cement kiln (scenario 2)			
Input			
Energy for grinding	MJ	3,466.43	Electricity, medium voltage {IT}| market for electricity, medium voltage | Cut-off, U
Distance from wind farm to treatment plant (200 km)	kg*km	2,567,723.08	Transport, freight, lorry >32 metric ton, EURO6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Cut-off, U
Alternative distance (AD) from wind farm to treatment plant (400 km)	kg*km	5,135,446.154	Transport, freight, lorry >32 metric ton, EURO6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | Cut-off, U
Alternative distance (AD) from wind farm to treatment plant (400 km with a smaller truck) (Option A)	kg*km	5,135,446.154	Transport, freight, lorry 3.5-7.5 metric ton, EURO6 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO6 | Cut-off, U
Output			
Power of the entire wind farm	MW	1	
Replaced carbon*	kg	5,068.96	Hard coal briquettes {RER}| hard coal briquettes production | Cut-off, U
Replaced inert material (sand)*	kg	5,763.25	Sand {RoW}| market for sand | Cut-off, U

** Such material is modelled in thesystem as avoided product* the use of coal for the combustion process (avoided product). In this way, it was taken into account that the amount of polymer organic component totally replaces the amount of coal necessary for the combustion process, also assuming that the furnace, for its operation, does not need any other fuel.

In order to calculate the amount of coal replaced, the energy content of both the GFRP waste material and the coal was considered: in detail, the higher calorific values were assumed to be 33.5 MJ/kg for the former and 28 MJ/kg for the latter (Karuppannan Gopalraj et al., 2021). In this way, the quantity of coal replaced by 1 kg of GFRP waste material is equal to 1,196 kg.

This environmental benefit was then included in the LCA modelby using a specific Ecoinvent dataset for the production of coal, considering it as avoided impact.

Finally, it was assumed, similarly to mechanical recycling, that the fibrous mineral component of the GFRP waste material can be used as a filler for clinker production, and the substituted product is sand, because it is a silica-rich material (avoided product). It was therefore considered that the substitution factor is 1:1, i.e. 1 kg of GFRP waste material, which contains 0.67 kg of fibrous mineral component, rich in components such as silica, replaces 0.67 kg of sand, a material rich in silica.

Table 1 summarizes the data and parameters used in Scenario1 and 2. Table 2 shows the input and output data used to model Scenario 1 and 2, and the Ecoinvent datasets used.

3. ENVIRONMENTAL IMPACT ASSESSMENT

3.1 Characterisation and normalisation results

Table 3 shows the results of characterization and normalization related to the treatment of GFRP waste material, referring to 1 MW of the entire wind farm, for the Scenario 1 (mechanical recycling) and for the Scenario 2 (co-processing in cement kiln).

4. RESULTS AND DISCUSSION

The analysis of normalization results shows that the most relevant impact categories (i.e. those categories that contribute cumulatively to 80% of the total normalisation results) are, for Scenario 1, "Resource use, fossils" (28% of the total normalisation phase), "Climate change" (15%), "Eutrophication, freshwater" (9%), "Ecotoxicity, freshwater", "Particulate matter", Photochemical ozone formation (8% each), and "Human toxicity cancer" (6%) (Table 3, Figure 2).

For the same relevant impact categories, an increase in impacts ranging from 44% to 111% is observed when considering the transport of the material over an alternative distance of 400 km (AD). From this it can be concluded that an increase in the distance of transport in this scenario has a significant environmental impact.

The most significant impact categories for Scenario 2 are" Eutrophication, freshwater" (-46% of the total normalisation phase), "Resource use, fossils" (-26%), "Ecotoxicity, freshwater" (-6%), "Photochemical ozone formation (-4%), "Acidification" and" Eutrophication, marine" (-3% each) (Table 3, Figure 3).

In Scenario 2, an increase in transport distance (AD) causes a non-significant decrease in avoided impacts for the main impact categories. Using a lower capacity means of transport to transport the material over the same distance (Option A) contributes significantly to the reduction in avoided impacts, but is still negligible given the high contribution of avoided impacts in the process.

As regards to characterisation results, the comparison between the two scenarios will be presented in the follow-

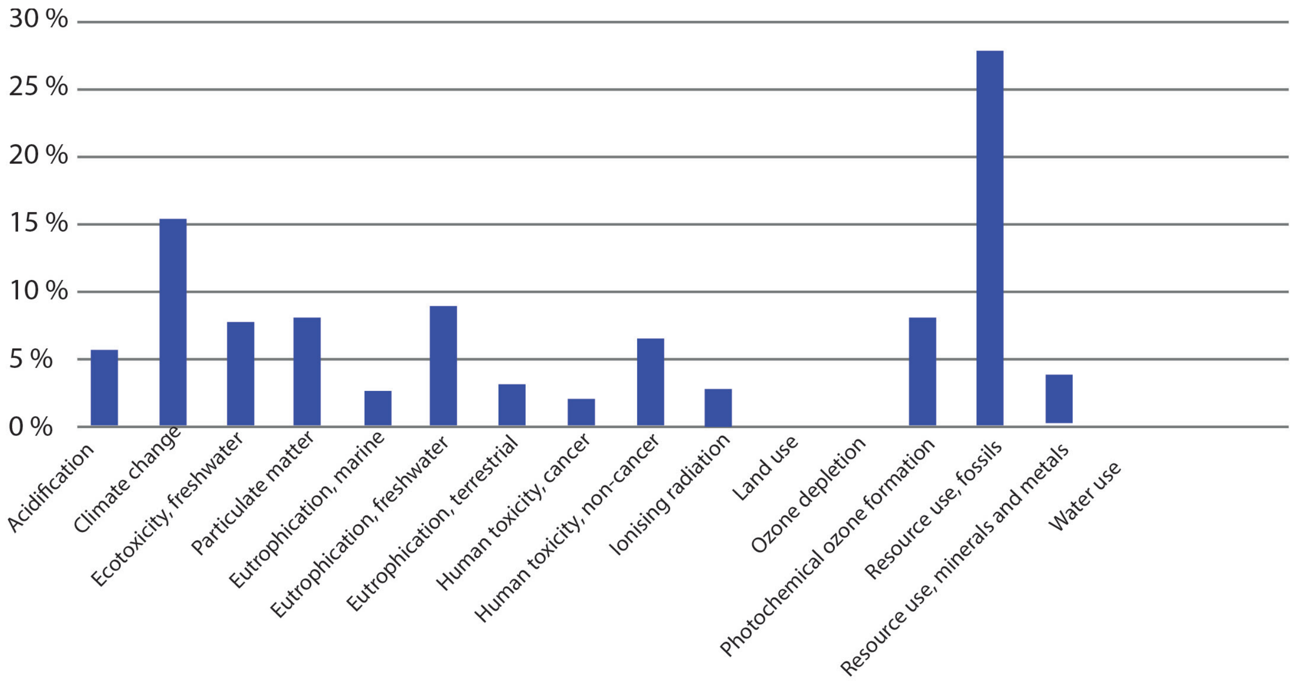

FIGURE 2: Normalisation results for Scenario 1 (mechanical recycling).

TABLE 3: Characterization and Normalization results related to GFRP waste material treatment, referring to 1 MW of the entire wind farm: Scenario 1 (mechanical recycling) and Scenario 2 (co-processing in cement kiln).

Impact category	Unit	Scenario 1		Scenario 2	
Characterization		**200 km**	**400 km (AD)**	**200 km**	**400 km (AD)**
Acidification	mol H+ eq	1.50E+00	2.14E+00	-1.33E+01	-1.26E+01
Climate change	kg CO_2 eq	5.69E+02	8.26E+02	-1.37E+03	-1.12E+03
Climate change-Biogenic	kg CO_2 eq	4.57E+00	4.65E+00	3.55E+00	3.63E+00
Climate change-Fossil	kg CO_2 eq	5.64E+02	8.22E+02	-1.38E+03	-1.12E+03
Climate change-LU and LU change	kg CO_2 eq	1.33E-01	2.58E-01	-1.29E+00	-1.17E+00
Ecotoxicity. freshwater-part 1	CTUe	1.50E+03	2.88E+03	-2.19E+04	-2.05E+04
Ecotoxicity. freshwater-part 2	CTUe	6.29E+02	1.13E+03	-3.42E+03	-2.93E+03
Ecotoxicity. freshwater-inorganics	CTUe	1.94E+03	3.75E+03	-2.50E+04	-2.32E+04
Ecotoxicity. freshwater-organics-p.1	CTUe	3.97E+01	5.47E+01	-9.15E+01	-7.66E+01
Ecotoxicity. freshwater-organics-p.2	CTUe	1.45E+02	2.03E+02	-2.31E+02	-1.73E+02
Particulate matter	disease inc.	2.30E-05	4.85E-05	-7.70E-05	-5.15E-05
Eutrophication. marine	kg N eq	2.31E-01	4.04E-01	-5.03E+00	-4.86E+00
Eutrophication. freshwater	kg P eq	6.91E-02	8.81E-02	-5.87E+00	-5.86E+00
Eutrophication. terrestrial	mol N eq	2.51E+00	4.29E+00	-4.63E+01	-4.45E+01
Human toxicity. cancer	CTUh	1.62E-07	2.76E-07	-1.01E-06	-8.91E-07
Human toxicity. cancer-inorganics	CTUh	7.97E-08	1.36E-07	-7.91E-07	-7.35E-07
Human toxicity. cancer-organics	CTUh	8.22E-08	1.41E-07	-2.14E-07	-1.56E-07
Human toxicity. non-cancer	CTUh	3.97E-06	6.76E-06	-4.22E-05	-3.94E-05
Human toxicity. non-cancer-inorg.	CTUh	3.77E-06	6.41E-06	-4.07E-05	-3.81E-05
Human toxicity. non-cancer-org.	CTUh	2.04E-07	3.46E-07	-1.53E-06	-1.39E-06
Ionising radiation	kBq U-235 eq	5.22E+01	5.72E+01	-3.88E+01	-3.39E+01
Land use	Pt	4.64E+01	4.01E+03	-1.74E+04	-1.34E+04
Ozone depletion	kg CFC11 eq	1.33E-05	1.92E-05	-2.35E-05	-1.77E-05
Photochemical ozone formation	kg NMVOC eq	1.58E+00	2.62E+00	-1.29E+01	-1.18E+01
Resource use. fossils	MJ	8.91E+03	1.28E+04	-1.32E+05	-1.28E+05
Resource use. minerals and metals	kg Sb eq	1.11E-03	1.83E-03	-6.40E-04	7.92E-05
Water use	m3 depriv.	-6.03E+00	1.26E+01	-1.36E+02	-1.17E+02
Normalization					
Acidification	-	2.70E-02	3.85E-02	-2.39E-01	-2.27E-01
Climate change	-	7.53E-02	1.09E-01	-1.82E-01	-1.48E-01
Ecotoxicity. freshwater	-	3.76E-02	7.06E-02	-4.46E-01	-4.13E-01
Particulate matter	-	3.86E-02	8.14E-02	-1.29E-01	-8.66E-02
Eutrophication. marine	-	1.18E-02	2.07E-02	-2.57E-01	-2.49E-01
Eutrophication. freshwater	-	4.30E-02	5.48E-02	-3.66E+00	-3.64E+00
Eutrophication. terrestrial	-	1.42E-02	2.43E-02	-2.62E-01	-2.52E-01
Human toxicity. cancer	-	9.38E-03	1.60E-02	-5.83E-02	-5.16E-02
Human toxicity. non-cancer	-	3.08E-02	5.25E-02	-3.28E-01	-3.06E-01
Ionising radiation	-	1.24E-02	1.35E-02	-9.20E-03	-8.03E-03
Land use	-	5.66E-05	4.89E-03	-2.12E-02	-1.64E-02
Ozone depletion	-	2.55E-04	3.66E-04	-4.49E-04	-3.37E-04
Photochemical ozone formation	-	3.86E-02	6.40E-02	-3.15E-01	-2.90E-01
Resource use. fossils	-	1.37E-01	1.97E-01	-2.03E+00	-1.97E+00
Resource use. minerals and metals	-	1.74E-02	2.87E-02	-1.01E-02	1.24E-03
Water use	-	-5.26E-04	1.10E-03	-1.19E-02	-1.02E-02

ing paragraphs, focusing only on the impact categories relevant for both treatment processes (i.e. “Resource use, fossils”, Eutrophication, freshwater”, “Ecotoxicity freshwater” and “Particulate matter”). Moreover, “Climate change” category is added to the discussion, due to its global relevance.

The results of “Climate change” and “Resource use, fossils” for Scenario 2 (co-processing in a furnace for the production of cement), equal to -1.37E+03 kg CO_2eq. and -1.32E+05 MJ respectively”, highlight that its avoided impacts are much higher than the results of Scenario 1 (mechanical recycling), where “Climate Change” is equal to 5.69E+02 kg CO_2eq., and “Resource use, fossils” is equal to 8.91E+03 MJ (Table 3, Figure 4, Figure 5). Scenario 2 is therefore more environmentally sustainable and this is due to the higher avoided impacts, which are affected by coal substitution in the co-processing.

As regards to “Eutrophication freshwater”, the characterisation result for Scenario 1 is 6.91E-02 kgPeq. (positive value), whereas it is -5.87E+00 kgPeq. (negative value) for Scenario 2: the latter therefore is an avoided impact. More in detail (Figure 6), the two processes that most affect the results of this impact category are the electricity consumption to grind the GFRP waste material in Scenario 1 (6.07E-02 kg P eq.) and the avoided impacts from coal substitution in Scenario 2 (-5.94E+00 kg P eq.). On the contrary, the contributions of transport and the use of recycled material to replace sand are negligible.

The characterisation results of “Ecotoxicity freshwater” and “Photochemical ozone formation” show that, similarly to the other impact categories, the impact differences for the two treatment processes are strongly affected by coal substitution in the co-processing. Figure 7 and Figure 8 show that the avoided impacts of the replaced coal in Scenario 2 are equal to -2.74E+04 CTUe in “Ecotoxicity freshwater” and equal to -1.45E+01 kg NMVOC eq. in “Photochemical ozone formation”, whereas the avoided impacts from the substitution of the sand in Scenario 1 are equal to -4.93E+02 CTUe in “Ecotoxicity freshwater” and equal to -6.12E-01 kg NMVOC eq. in “Photochemical ozone formation”. The avoided impacts of sand substitution in Scenario 1 have therefore the same order of magnitude of the avoided impacts of sand substitution in Scenario 2, where they are equal to -4.89E+02 CTUe in “Ecotoxicity freshwater” and -6.07E-01 kg NMVOC eq. in “Photochemical ozone formation”.

5. CONCLUSIONS

The LCA study of the two scenarios for the treatment of GFRP waste material contained in wind turbines shows that mechanical recycling (Scenario 1) has significantly higher environmental impacts than co-processing in cement kiln (Scenario 2), because in the latter the avoided impacts have a much higher value. This is mainly due to the fact that in the co-processing, in addition to the valorisation of the recycled secondary material at the end of the treatment process, the energy needed for the process is provided by the polymer organic component of the GFRP waste mate-

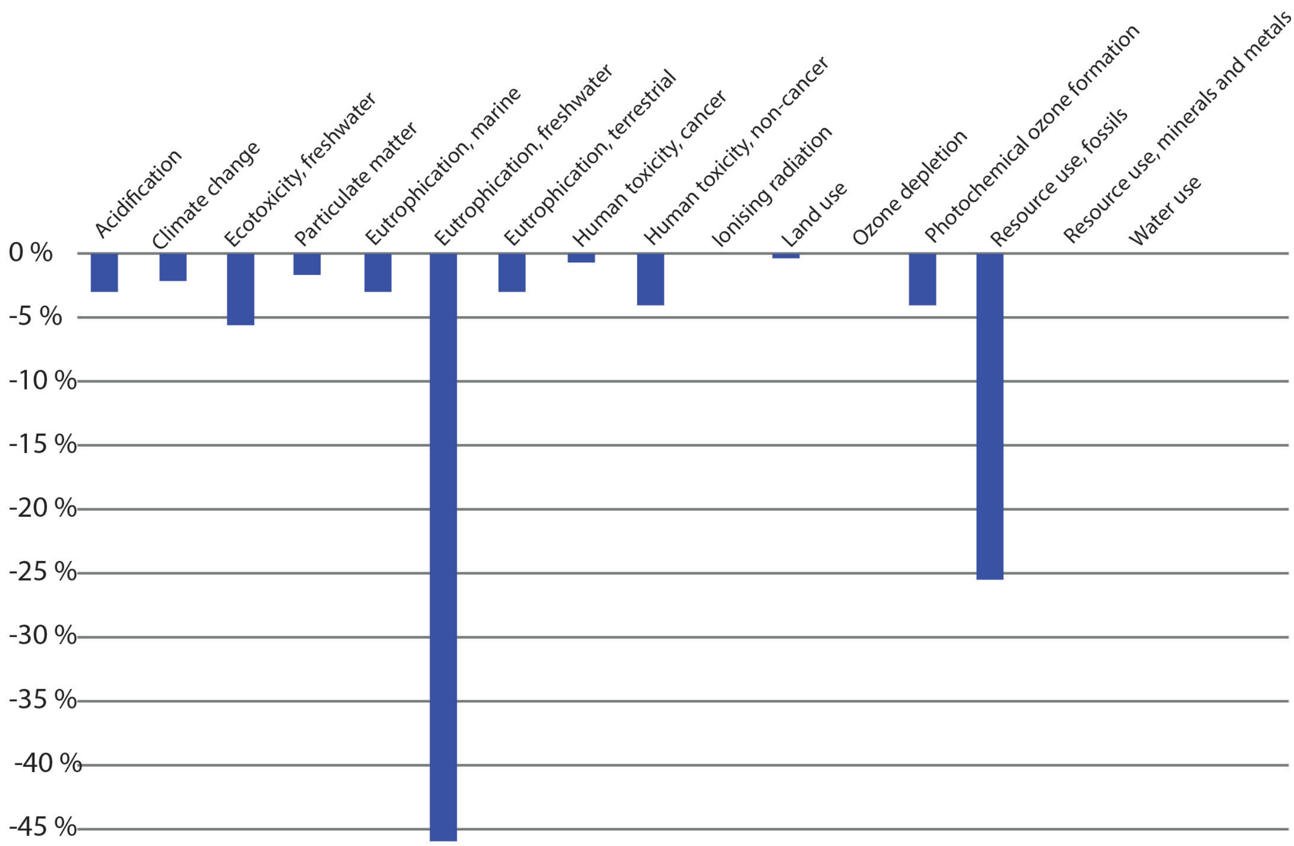

FIGURE 3: Normalization results for Scenario 2 (co-processing in a cement kiln).

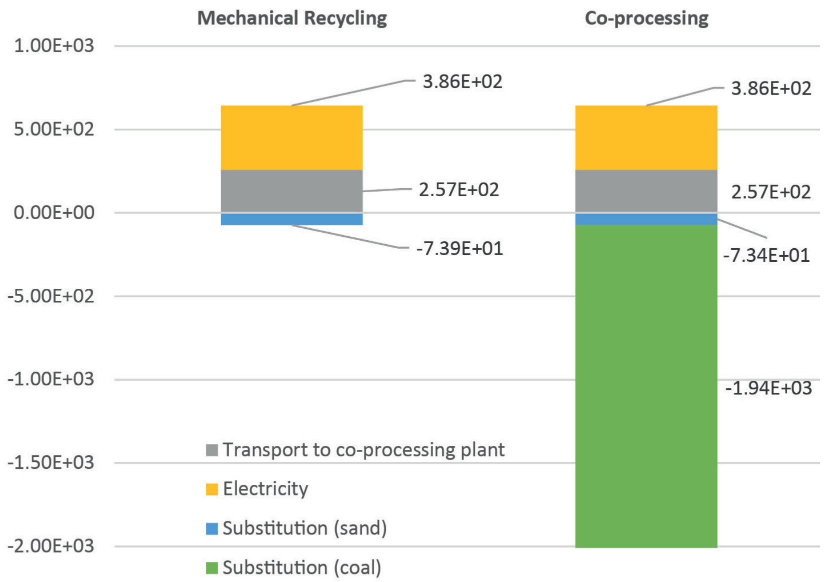

FIGURE 4: Climate change characterisation results (kg CO_2 eq) for both scenarios. Process contribution of the GFRP waste material treatment.

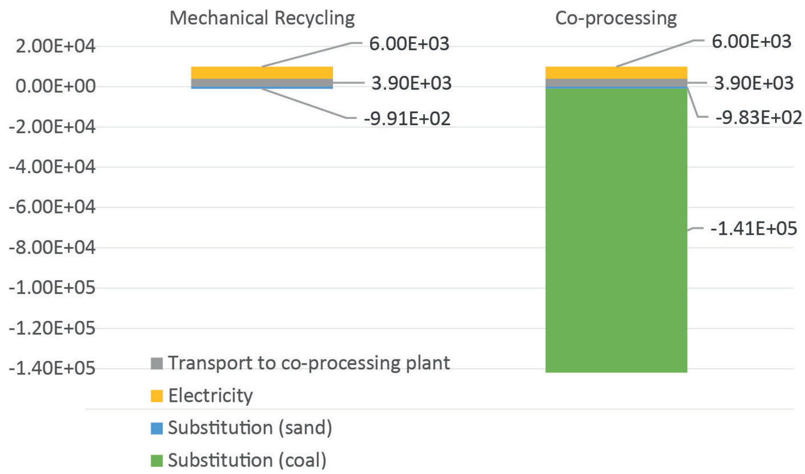

FIGURE 5: Characterisation results of the category Resource use, fossils (MJ) eq) for both scenarios GFRP - Process contributions of the GFRP waste material treatment.

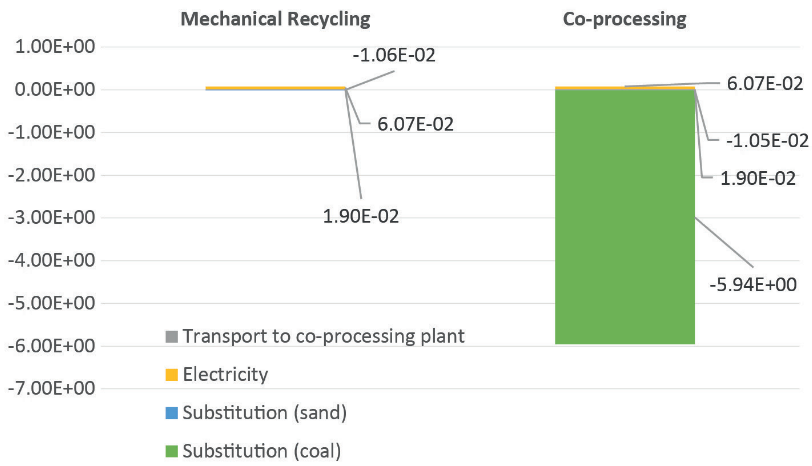

FIGURE 6: Characterisation results of the category Eutrophication freshwater (kg P eq) for both scenarios – Process contributions of the GFRP waste material treatment.

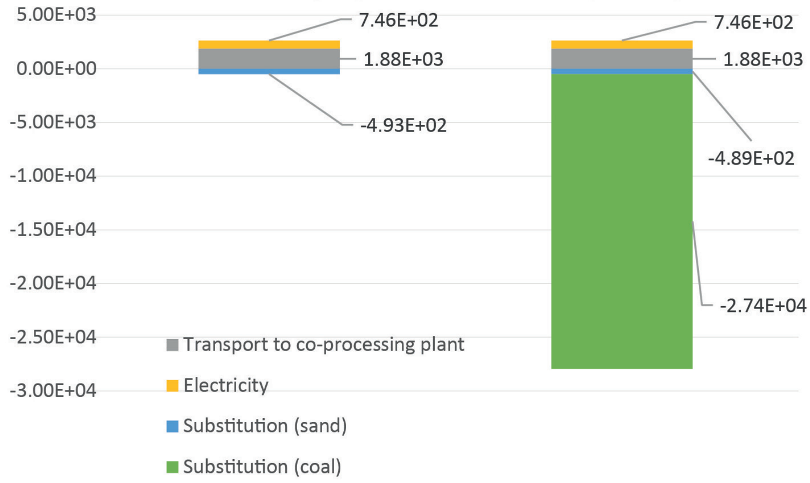

FIGURE 7: Characterisation results of the Ecotoxicity category freshwater (CTUe) for both scenarios - Process contributions of the GFRP waste material treatment.

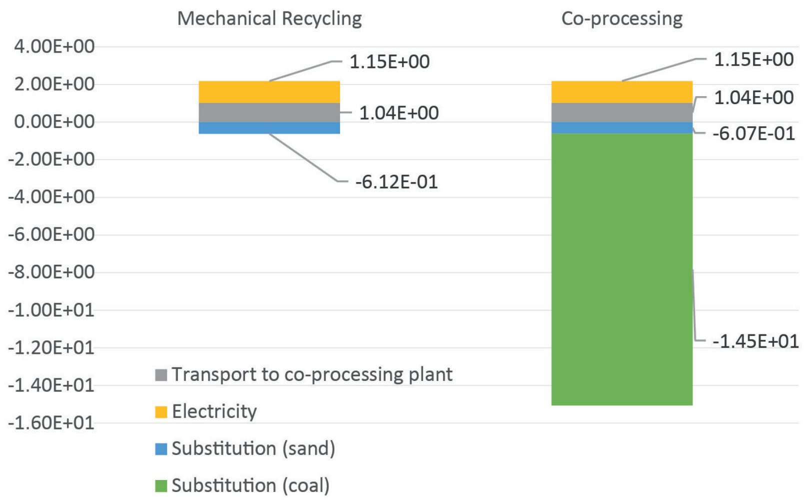

FIGURE 8: Characterisation results of the Photochemical ozone formation (kg NMVOC eq) category for both scenarios - Process contributions of the GFRP waste material treatment.

rial, thus avoiding the production of a similar quantity of coal, which would be necessary for the combustion inside the furnace. In fact, the GFRP waste material, due to its polymer component, has a higher calorific value than the replaced fuel. In this way, the co-processing is more environmentally friendly than mechanical recycling, especially in "Resource use, fossils" (Scenario 1: 8.91E+03 MJ; Scenario 2: -1.32E+05 MJ) and "Climate change" (Scenario 1: 5.69E+02 kg CO_2eq. Scenario2: 1.37E+03 kg CO_2eq.) impact categories.

The analysis of characterisation results shows that also the other relevant impact categories results are affected by the valorisation of GFRP waste material: this is evident in Scenario 2, where coal to feed the process is replaced by the same waste material. In fact, the avoided impacts of "Eutrophication freshwater", "Ecotoxicity freshwater" and "Photochemical ozone formation" in Scenario 2 are higher than in Scenario 1, where only sand is replaced by the GFRP waste material at the end of the mechanical treatment.

Finally, the literature analysis (Yazdanbakhsh et al., 2014) highlights that mechanical recycling has a low energy consumption but, on the other hand since it does not separate the polymer organic component and the fibrous mineral component, it produces a recycled material with poor mechanical properties which is suitable for limited use as a filler or reinforcement in construction. Therefore, this type of treatment produces a barely valuable material if compared to the physical properties and functions of the virgin GFRP material. In order to increase its valorisation potential, the material must undergo further processing, with a greater expenditure of energy, to finally obtain a "fine" grade material, usable as filler for the production of new composites, for example as a secondary material in the production of thermoplastics.

On the contrary, co-processing in cement kilns is a highly efficient process because it can recover energy from the waste material and can integrate part of it into the clinker production process. Nevertheless, the fibrous mineral component of the GFRP waste material lose its physical form during the process, and this makes its recovery difficult for more valuable applications, such as the production of new composite materials.

In conclusion, the results of this LCA study provide some general considerations about the possible recycling and recovery of GFRP material contained in wind turbine blades, including also an assessment of the environmental benefits obtainable through the secondary material valorisation. These outcomes could therefore be used for future in-depth analysis, by means of the realisation of further LCA studies on recycling and recovery technologies based on primary data. Finally, they could support the definition of ecodesign strategies also useful for improving the environmental performance of wind farms life cycle, taking also into account the dismantling and waste treatment phases, in order to increase recyclability of its components and materials and so the overall circularity of the system.

REFERENCES

3D Wall Panels Italia 3D Wall Panels Italia [Online] / prod. CM PRODUCT GROUP SRL. - 2024. - https://it.3dwallpanels-italia.com/.

Chen Shanshan [et al.] Promoting Interspecies Electron Transfer with Biochar [Journal] // Scientific Reports. - 2014. - 5019 : Vol. 4.

European Commission - Joint Research Centre Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD) Handbook Specific guide for Life Cycle Inventory data sets. First edition March 2010 [Book]. - Luxembourg. : Office of the European Union, 2010.

European Commission PEFCR Guidance document, - Guidance for the development of Product Environmental Footprint Category Rules (PEFCRs), version 6.3 [Report]. - 2017.

Gees Recycling Gees Recycling [Online] / prod. Gees Recycling Srl ©. - 2024. - https://www.geesrecycling.com/brevetto-compounding-recycling.asp.

Gonçalves R.M., Martinho Alberto and Oliveira J.P. Recycling of Reinforced Glass Fibers Waste: Current Status [Journal] // Materials. - 2022. - 4 : Vol. 15.

Howarth J, Mareddy Sada S.R. and Mativenga Paul T. Energy intensity and environmental analysis of mechanical recycling of carbon fibre composite [Journal] // Journal of Cleaner Production. - 2014. - Vol. 81. - pp. 46-50.

IEA World Energy Outlook 2023 [Report]. - Paris : Licence: CC BY 4.0 (report); CC BY NC SA 4.0, 2023.

Jacob Amanda Composites can be recycled [Journal] // Reinforced Plastics. - May-June 2011. - 3 : Vol. 55. - pp. 45-46.

Karuppannan Gopalraj Sankar [et al.] Life Cycle Assessment of a Thermal Recycling Process as an Alternative to Existing CFRP and GFRP Composite Wastes Management Options [Journal] // Polymers. - 2021. - 24 : Vol. 13.

Krauklis Andrey E. [et al.] Composite Material Recycling Technology—State-of-the-Art and Sustainable Development for the 2020s [Journal] // Special Issue From Waste to Advance Composite Materials. - 2021. - 1 : Vol. 5.

Liu Pu , Meng Fanran e Barlow Claire Y. Wind turbine blade end-of-life options: An eco-audit comparison [Journal] // Journal of Cleaner Production. - 2019. - Vol. 212. - p. 1268-1281.

Liu Pu , Meng Fanran and Barlow Claire Y. Wind turbine blade end-of-life options: An economic comparison [Journal]. - 2022. - Vol. 180. - pp. 106-202.

Oliveux Géraldine , Dandy Luke O. and Leeke Gary A. Current status of recycling of fibre reinforced polymers: Review of technologies, reuse and resulting properties [Journal] // Progress in Materials Science. - 2015. - Vol. 72. - pp. 61-99.

Palmer James Alexander Thomas Mechanical Recycling of Automotive Composites for Use as Reinforcement in Thermoset Composites [Report]. - Exeter : University of Exeter, 2009.

UNI UNI EN ISO 14040:2021 Gestione ambientale - Valutazione del ciclo di vita - Principi e quadro di riferimento. - 2021a.

UNI UNI EN ISO 14044:2021 Gestione ambientale - Valutazione del ciclo di vita - Requisiti e linee guida.. - 2021b.

Vestas, Wind Systems 2 MW platform [Online]. - 2024. - june 3, 2024. - https://nozebra.ipapercms.dk/Vestas/Communication/Productbrochure/2MWTurbineBrochure/2mw-platform-brochure/?page=1.

Wernet Gregor [et al.] The ecoinvent database version 3 (part I): overview and methodology [Journal] // Int J Life Cycle Assess. - 2016. - Vol. 21. - pp. 1218-1230.

Wind Europe Decommissioning of Onshore Wind Turbines - Industry Guidance Document [Report]. - [s.l.] : Rory O'Sullivan, 2020.

WindEurope – Cefic - EuCIA Accelerating Wind Turbine Blade Circularity - 2020 [Report]. - 2020.

Yazdanbakhsh Ardavan and Bank Lawrence C. A Critical Review of Research on Reuse of Mechanically Recycled FRP Production and End-of-Life Waste for Construction [Journal] // Polymers - Special Issue Fiber-Reinforced Polymer Composites in Structural Engineering. - 2014. - 6 : Vol. 6. - pp. 1810-1826.

Zampori Luca and Pant Rana Suggestions for updating the Product Environmental Footprint (PEF) method [Report] / European Commission - JRC. - Luxembourg : Publications Office of the European Union, 2019.