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ORIGINAL ARTICLE

Blade manufacturing for onshore and offshore wind farms: the energy and environmental performance for a case study in Brazil

Manufatura de pás para parques eólicos onshore e offshore: o desempenho energético e ambiental para um estudo de caso no Brasil

Mário Joel Ramos Júnior[1], Diego Lima Medeiros[2], Edna dos Santos Almeida[1]

[1] Centro Universitário Senai Cimatec, Área de Meio Ambiente, Salvador, BA, Brasil. E-mail: ramosjuniormariojoel@gmail.com; ednasa@fieb.org.br

[2] Universidade Federal do Maranhão – UFMA, Balsas, MA, Brasil. E-mail: diegomedeiros350@gmail.com

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Abstract: This study aims to analyze the energy and environmental performance of the manufacture of two models of wind turbine blades for a 300 MW wind farm. Material flow analysis (MFA) was used to prepare the mass balance, while life cycle assessment (LCA), based on ISO-14044, was used to evaluate three impact categories, considering sensitivity analysis to evaluate the replacement of wind turbine blade materials. Results showed that the manufacturing of wind turbine blades causes a 10% loss of material impregnated with fiberglass and epoxy resin. Fiberglass was the input with the highest contribution to water consumption, energy consumption, and the carbon footprint. The sensitivity analysis showed that, for the offshore scenario of higher capacity factor and longer lifetime, the carbon footprint contribution per electricity to be produced was 0.214 kg CO_2eq/GJ, while for the onshore scenario of lower capacity factor and shorter lifetime, it was 1.37 kg CO_2eq/GJ. When using jute fiber grown without irrigation as a substitute input for fiberglass, the reduction was 38% (onshore) and 42% (offshore) in water consumption, 18% (onshore and offshore) in energy consumption, and 24% (onshore) and 25% (offshore) in carbon footprint. The onshore model had a larger impact in all the categories evaluated than the offshore model. Therefore, the use of unirrigated jute fiber allows gains in energy and environmental performance.

Keywords: Renewable energy; Wind energy; Life cycle assessment; Environmental performance; Wind turbine blades; Composite material.

Resumo: Este estudo tem como objetivo analisar o desempenho energético e ambiental da manufatura de dois modelos de pás de turbina eólica para compor um parque eólico de 300 MW. A Análise de Fluxo de Material (AFM) foi utilizada para elaborar o balanço de massa, enquanto a Avaliação do Ciclo de Vida (ACV) baseada na NBR ISO-14044 foi utilizada para avaliar três categorias de impacto, na qual a análise de sensibilidade foi considerada para avaliar a substituição de materiais da pá de turbina eólica. Os resultados indicaram que a manufatura das pás de turbina eólica gera uma perda de 10% de material impregnado com fibra de vidro e resina epóxi. A fibra de vidro foi o insumo que apresentou a maior contribuição em relação ao consumo de água, consumo de energia e pegada de carbono. A análise de sensibilidade evidenciou que, para o cenário *offshore* de maior fator de capacidade e maior vida útil, a contribuição da pegada de carbono por eletricidade a ser produzida foi 0,214 kg CO_2eq/GJ, enquanto para o cenário de *onshore* de menor fator de capacidade e menor vida útil foi 1,37 kg CO_2eq/GJ. Ao se

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utilizar a fibra vegetal de juta cultivada sem irrigação como um insumo substituto da fibra de vidro, a redução do consumo de água é de 38% (*onshore*) e 42% (*offshore*), do consumo de energia é de 18% (*onshore* e *offshore*) e da pegada de carbono é de 24% (*onshore*) e 25% (*offshore*). O modelo *onshore* apresentou um maior impacto que o *offshore* em todas as categorias avaliadas. Portanto, é possível obter ganhos no desempenho energético e ambiental empregando fibra vegetal de juta não irrigada.

Palavras-chave: Energia renovável; Energia eólica; Avaliação do ciclo de vida; Desempenho ambiental; Pá de turbina eólica; Material compósito.

1 Introduction

In 2019, 27% of the world's electricity came from renewable sources, while 73% came from non-renewable sources (IEA, 2022). Coal, oil, and natural gas are used as fuel in the traditional energy production system. These materials have many hydrocarbons, which, when burned, release CO_2 and other greenhouse gases. According to Mello et al. (2020), who used life cycle assessment (LCA) to compare energy production cycles, as wind energy produces less emissions and environmental impacts during the operation phase than fossil fuel energy, it is considered a "cleaner" generation source.

With an average annual growth rate of 13% for installed capacity from 2011 to 2021, wind energy is one of the fastest growing sources of power generation in the world (Cooperman et al., 2021; GWEC, 2022). The number of wind farms installed in Brazil has increased significantly in recent years. According to ABEEÓLICA (2022), this capacity expanded from 1 524 MW in 2011 to 21 577 MW in 2021, which implies an average growth rate of 30% per year. Moreover, according to ABEEÓLICA (2022), Northeastern Brazil, which includes the states of Rio Grande do Norte, Bahia, Piauí, and Ceará, accounted for 88.7% of all wind energy produced in Brazil in 2021.

The basic parts of a wind turbine are the foundation, tower, blades, rotor, hub, shaft, nacelle, and generator (ABDI, 2017). More powerful wind turbines and larger-scale wind farms are needed to harness more wind energy and lower the cost of electricity generation. Structural components must meet design requirements for stiffness, mechanical and fatigue strength, environmental durability, light weight, low cost, and the availability of end-of-life recycling solutions (Müssig et al., 2020). For both onshore and offshore models, the energy production and lifetime of wind turbines significantly affect the intensity of greenhouse gas emissions (Wang et al., 2019a).

In the case of wind farms, the most significant environmental impact concerns the major components, such as towers, foundations, and blades, which consume the most electricity during manufacture, resulting in indirect emissions. The installation and operation stages contribute little to emissions (Chipindula et al., 2018). Gomaa et al. (2019) found that the manufacturing stage accounted for the greatest impact, 91% of global warming and 64% of cumulative energy demand, when evaluating wind farms using the LCA method. The manufacturing stage contributes almost 90% of the total emissions of the entire wind farm life cycle (Mello et al., 2020). Regarding wind turbine blades, the production of the materials - mainly fiberglass and epoxy resin - represents their largest contribution to greenhouse gas emissions (Chiesura et al., 2020).

Except for wind turbine blades, which are composites and often have a high proportion (60–70%) of fiber reinforced polymer (FRP) or carbon fiber reinforced polymer (CFRP), most wind turbine components are recycled (Deeney et al., 2021; Jensen & Skelton, 2018). Thus, their final destination is a major source of environmental concern (EPE, 2021). The recycling of thermoset FRP blades from mechanical and thermochemical processes has received more attention as a result of the increasing number of wind turbine blades reaching the end of their lifetime and concerns about resource conservation and environmental protection (Dorigato, 2021).

However, after reaching the end of their lifetime, wind turbine blades are often disposed in landfills or burned (Ramos & Almeida, 2021). The National Solid Waste Policy guidelines (Brasil, 2010) and the list of waste management priorities required to create a circular economy, which follows the model of Directive 2008/98/EC of the European Parliament and the European Council (European Union, 2008), place these two solutions at the bottom levels of the hierarchy. The aforementioned studies showed that the growth of the wind industry and the alternatives for disposal after use led to an increase in composite materials use. However, no actions were suggested to decrease the sources that generate waste or affect the energy and environmental performance of the inputs used in wind energy.

Thus, this study aims to analyze the energy and environmental performance of the manufacture of two models of wind turbine blades (onshore and offshore). We used material flow analysis (MFA) to prepare the mass balance, LCA to evaluate energy and environmental performance, and sensitivity analysis to evaluate the replacement of wind turbine blade materials.

2 Methodology

This study evaluated wind turbine blades for onshore and offshore wind farms, made of composite material and manufactured in the Pecém Industrial and Port Complex (CIPP – Complexo Industrial e Portuário do Pecém) in Caucaia, Ceará, Brazil. MFA (Brunner & Rechberger, 2003) and LCA, based on ISO-14044 (ABNT, 2009), were the methods used. The annual output of the factory was considered sufficient to supply a wind farm with a nominal capacity of 300 MW (on-demand manufacturing). Two wind turbine blade models (onshore and offshore) were analyzed. The purpose of wind turbine blades is to collect the kinetic energy of the wind, which is then transformed into mechanical energy.

The production of wind turbine blades for a wind farm with a nominal capacity of 300 MW is the functional unit considered in this study. Since each wind turbine in the onshore model has a rated output power of 4 MW, this model requires 75 wind turbines and 225 wind turbine blades. The Chinese company MingYang Defeng Energy Systems CO.LTD is the manufacturer of the MySE4.0-145 wind turbine. The rotor has a diameter of 145 m, a surface area of 16 505 m^2, a nominal weight of 19.7 t, and three blades (Bauer & Matysik, 2022).

The offshore model required 25 wind turbines and 75 wind turbine blades, since each wind turbine has a rated output power of 12 MW. General Electric (GE) Renewable Energy manufactures the Haliade-X wind turbine in Germany. The rotor has a diameter of 220 m, a surface area of 38,000 m^2, a nominal weight of 55 t, and three blades (Bauer & Matysik, 2022).

The STAN program version 2.7.101 was used to complete MFA, which was initiated for the onshore model by Ramos et al. (2022) and complemented for the offshore model in this study. According to the Austrian standard ÖNORM S 2096 (Material flow analysis – Part 1: Application in waste management), STAN (short for subSTance flow ANalysis) is a free software used for MFA (TUV, 2022). Figure 1 shows the product system evaluated in this study.

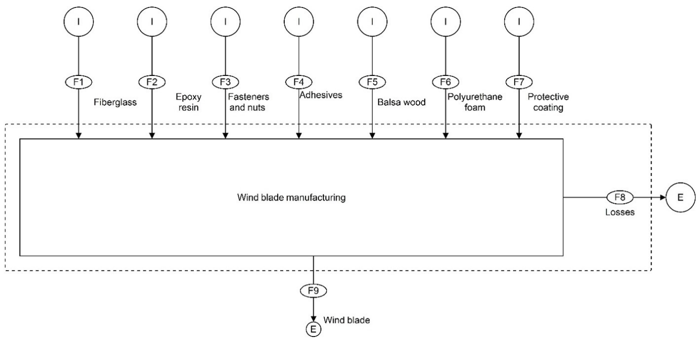

Figure 1. Product system: manufacture of wind turbine blades. The flows are classified as import (I) or export (E).

2.1 Transportation inventory

In total, 225 wind turbine blades were manufactured for the onshore model and 75 for the offshore model. Table 1 presents the quantities of material (Q, in t) and the distance (d, in km) over which they were transported from the suppliers' exit gates to the manufacturer's entrance gates in Ceará. The Brazilian Agency for Industrial Development provided information about the location of the main suppliers of the raw materials used to manufacture the Brazilian wind turbine blades (ABDI, 2017).

Table 1. Supplier transportation inventory for the manufacture of wind turbine blades.

Base scenario						Onshore (225 pieces)			Offshore (75 pieces)		
Parameter	Supplier	Transport type	Place of origin	Place of destination	d (km)	Q (t)	Q × d (t.km)	Q × d × 2 (t.km)	Q (t)	Q × d (t.km)	Q × d × 2 (t.km)
Fiberglass	CPIC Brasil	Truck	Capivari (Brazil)	Caucaia (Brazil)	3 192	3 012	-	1.92E+7	2 803	-	1.79E+7
Epoxy resin	DOW	Truck	Guarujá (Brazil)	Caucaia (Brazil)	3 020	1 611	-	9.73E+6	1 499	-	9.05E+6
Metal fasteners and nuts	Tecnofix	Truck	Sorocaba (Brazil)	Caucaia (Brazil)	3 103	62	-	3.85E+5	58	-	3.60E+5
Adhesives	Henkel	Truck	Diadema (Brazil)	Caucaia (Brazil)	3 120	13	-	8.11E+4	12	-	7.49E+4
Balsa wood	INCOM Ingeniería de Compuestos	Truck	Alicante (Spain)	Port of Valencia (Spain)	152	102	-	6.83E+5	95	-	6.36E+5
Balsa wood	INCOM Ingeniería de Compuestos	Ship	Port of Valencia (Spain)	Port of Santos (Brazil)	8 509	102	8.68E+5	-	95	8.08E+5	-
Balsa wood	INCOM Ingeniería de Compuestos	Truck	Port of Santos (Brazil)	Caucaia (Brazil)	3 197	102	-	6.83E+5	95	-	6.36E+5
Polyurethane foam	3A Composites	Truck	Steinhausen (Switzerland)	Port of Hamburg (Germany)	910	75	-	6.16E+5	70	-	5.75E+5
Polyurethane foam	3A Composites	Ship	Port of Hamburg (Germany)	Port of Santos (Brazil)	10 159	75	7.62E+5	-	70	7.11E+5	-
Polyurethane foam	3A Composites	Truck	Port of Santos (Brazil)	Caucaia (Brazil)	3 197	75	-	6.16E+5	70	-	5.75E+5
Protective coating (paint)	Mankiewicz	Truck	Hamburg (Germany)	Port of Hamburg (Germany)	4	71	-	4.55E+5	66	-	4.23E+5
Protective coating (paint)	Mankiewicz	Ship	Port of Hamburg (Germany)	Port of Santos (Brazil)	10 159	71	7.21E+5	-	66	6.70E+5	-
Protective coating (paint)	Mankiewicz	Truck	Port of Santos (Brazil)	Caucaia (Brazil)	3 197	71	-	4.55E+5	66	-	4.23E+5
Losses	ASMOC Landfill	Truck	Caucaia (Brazil)	Caucaia (Brazil)	15	514	-	1.54E+4	478	-	1.43E+4

Where: d represents the distance traveled (km); Q represents the quantity of material (t); Q × d represents the ship cargo (t.km); Q × d × 2 represents the truck cargo (t.km).

For each model, the transportation cargo was estimated by multiplying the quantity of material by the distance traveled. For road transport, the distance value was doubled, considering that each supplier's fleet would handle the delivery and each truck would pick up the input at the port or at the wind turbine blades manufacturer before returning to its base. According to National Transit Council Resolution No. 882, it was determined that each vehicle is a semi-trailer truck measuring 2.60 m wide, 4.40 m high, and 14 m long, with 23 t total gross weight and a payload capacity of 14 t (Brasil, 2021). For transportation by ship, a short distance was considered since the ship would make more trips before returning to port of origin.

This study assumed that national inputs would be transported by the Brazilian highway system and imported inputs, after being transported by truck to the nearest port, would be shipped to the Port of Santos followed by the highway road network to the manufacturer of the wind blades.

2.2 Energy and environmental performance

The structure of the wind turbine blades evaluated in this study included fiberglass fabric, epoxy resin, metal fasteners and nuts, adhesives, balsa wood, protective coating (paint), and polyurethane foam (ABDI, 2017). Liu & Barlow (2016) estimated the percentage of material by weight of a wind turbine blade (Table 2). According to Giannetti et al. (2012), during the production process, the epoxy resin impregnates the fiberglass in a liquid state, which, as a result of a curing reaction, transforms into a solid state over time. Information provided by the manufacturers pointed that the total mass of each wind turbine blade was 20 t in the onshore model and 55 t in the offshore model (Bauer & Matysik, 2022). In line with the national manufacturer of wind turbine blades, the energy consumption of the onshore and offshore models per blade produced was 87 GJ (Aeris Energy, 2022).

Liquefied petroleum gas (LPG) is used in the forklifts, while diesel fuel is used in cranes, forklifts, and semi-trailer trucks that lift and move cargo. Electricity powers the machinery used to cut fiberglass fabrics, inject epoxy resin, run vacuum pumps to remove air from infusions, deburr surfaces, fix flaws (using hand tools such as sanders and drills), and apply the finishing touches (sanders and electric compressor for painting). Gasoline and ethanol are used in the vehicles that transport workers.

Table 2 presents the mass contribution of the materials used and the production inventory of one unit for each wind turbine blade included in this study. Appendix 1 (Table A1) shows that the basic uncertainty and the pedigree score (Weidema et al., 2013) were used to estimate the relative arithmetic standard deviation of the quantities.

Table 2. Foreground inventory of the manufacturing of a blade for onshore and offshore wind farms.

Parameter	Unit	Onshore wind turbine blade	Offshore wind turbine blade	Mass contribution	Reference
Input					
Fiberglass fabric	t	13.386 ± 13%	37.373 ± 13%	60.4%	Liu & Barlow (2016)
Epoxy resin	t	7.155 ± 13%	19.986 ± 13%	32.3%	Liu & Barlow (2016)
Metal fasteners and nuts	t	0.276 ± 13%	0.770 ± 13%	1.4%	Liu & Barlow (2016)
Adhesives	t	0.058 ± 13%	0.165 ± 13%	0.3%	Liu & Barlow (2016)
Balsa wood	t	0.453 ± 13%	1.265 ± 13%	2.3%	Liu & Barlow (2016)
Polyurethane foam	t	0.335 ± 13%	0.935 ± 13%	1.7%	Liu & Barlow (2016)
Protective coating (paint)	t	0.315 ± 13%	0.880 ± 13%	1.6%	Liu & Barlow (2016)
Energy, diesel	GJ	3.08 ± 5%	3.08 ± 5%	-	Aeris Energy (2022)

Table 2. Continued…

Parameter	Unit	Onshore wind turbine blade	Offshore wind turbine blade	Mass contribution	Reference
Energy, gasoline	GJ	0.92 ± 5%	0.92 ± 5%	-	Aeris Energy (2022)
Energy, LPG	GJ	2.39 ± 5%	2.39 ± 5%	-	Aeris Energy (2022)
Energy, ethanol	GJ	0.02 ± 5%	0.02 ± 5%	-	Aeris Energy (2022)
Energy, electricity	GJ	80.53 ± 5%	80.53 ± 5%	-	Aeris Energy (2022)
Transportation, truck	t.km	1.39E+5 ± 37%	3.87 E+5 ± 37%	-	Table 1
Transportation, ship	t.km	1.04E+4 ± 37%	2.92 E+4 ± 37%	-	Table 1
Output					
Losses (fiberglass and epoxy-impregnated material)	t	2.283 ± 11%	6.373 ± 11%	-	Giannetti et al. (2012); Papadakis et al. (2010)

t = tonne; GJ = Gigajoule; t.km = transport load.

The background inventory (Appendix 1-Table A1) was inserted in openLCA® version 1.11.0 using the Ecoinvent™ inventory database version 3.4. The following evaluation methods were also used: ReCiPe 2016 midpoint (H) for water consumption (m^3), cumulative energy demand (CED) for renewable and non-renewable energy consumption (GJ), and IPCC 2021 100-year global warming potential (GWP) for greenhouse gas (GHG) emissions in carbon dioxide equivalent (CO_2eq). As a result, ReCiPe 2016 midpoint (H) was modified to include “water emission to water/unspecified emission,” since the database version used did not consider the water that returns to the water body.

2.3 Sensitivity and variability analysis

The National Electric System Operator of Brazilian data for 2021 was used in the first sensitivity analysis to assess the impact of the capacity factor on energy and environmental performance under three different scenarios: lower capacity factors and lifetime; average historical capacity factors and lifetime; and higher capacity factors and lifetime (ONS, 2022). The average capacity factor (MW/MW) of onshore wind turbines in Brazil for 2021 was 44%; the lowest value was 31% in March and the highest value was 58% in August (ONS, 2022). The average value in Brazil was higher than the global average for the onshore model, which ranged from 20% to 35% (Liu & Barlow, 2016). The coastline between the states of Maranhão, Piauí, and Ceará has a 45% to 60% potential capacity factor for the offshore model (yet non-existent in Brazil). This information was considered in this study (Reis et al., 2021). Moreover, the average offshore capacity factor in Brazil was 53%.

The lifetime of a wind turbine blade is estimated to be 20 years (Cooperman et al., 2021; Liu & Barlow, 2016). According to EPE (2021), IEC 61400-1 (Wind energy generation systems – Part 1: Design requirements) suggests that the design of wind turbines has a minimum lifetime of 20 years, as this is the period considered in calculations, numerical modeling, laboratory tests with prototypes, mechanical strength testing of components, and field experiments that evaluate the history of equipment failures and breakdowns. The least desirable lifetime was 10 years, and the most desirable lifetime was 30 years.

In the second sensitivity analysis, the same mass quantity of jute fiber grown without irrigation was used in place of glass fiber to simulate the energy and environmental performance of the manufacture of wind turbine blades while maintaining all other parameters. The variability analysis was conducted to obtain the arithmetic standard deviation of the evaluated categories values from the Monte Carlo simulation with 500 interactions in openLCA®.

2.4 Electricity production

Due to variations in the capacity factor of wind turbine blades for different wind farms, wind farm electricity production ($Eprod$) was estimated to quantify the energy and environmental burden contribution per unit of production (GJ of electricity) over the lifetime of the wind farm. $Eprod$ is a function of the number of turbines (n), the rated power (P, in MW), the capacity factor (γ, in MW/MW), and the lifetime (t_s, in years). The turbine model affects the nominal power. The ratio of the theoretical total power produced in continuous operation and the actual power production is the capacity factor. Equation 1 was used to estimate the energy production (in GJ), considering 365 days per year and a 24-hour operation per day:

$$Eprod = n \times P \times \gamma \times t_s \times 24 \times 365 \times 3.6 \tag{1}$$

$Eprod$ is 83 255 040 GJ for the onshore model and 100 284 480 GJ for the offshore model in the base scenario. Equation 2 was used to estimate the energy and environmental performance of the manufacture of wind turbine blades per GJ of electricity to be produced in the onshore and offshore wind farm.

$$Du := \frac{Dt}{Eprod} \tag{2}$$

Where:
Du represents the unit performance of the rated category (category unit/GJ);
Dt represents the total performance of the evaluated category associated with the manufacture of wind farm blades (category unit);
$Eprod$ represents the electricity to be produced in the wind farm life cycle (GJ).

3 Results

3.1 Energy and environmental performance

Figures 2 and 3 shows the material flow for the wind turbine blades of a wind farm with a nominal capacity of 300 MW. In total, 225 wind turbine blades were manufactured for the onshore model and 75 for the offshore model, and 870 973 m^3 of water were consumed in the entire manufacturing process of wind turbine blades for the onshore model. The water consumption for the offshore model was 729 610 m^3. Table 3 presents the contribution of water consumption per foreground inventory flow for the manufacture of all wind turbine blades needed to meet the demand of the evaluated wind farm.

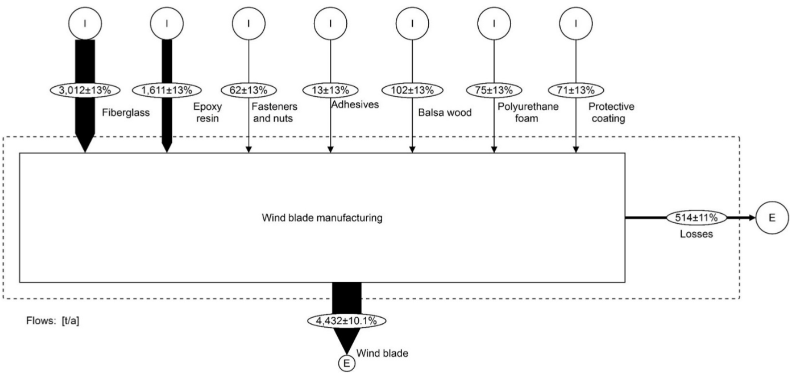

Figure 2. Material flow analysis of wind farm blades (onshore model). The flows are classified as import (I) or export (E).

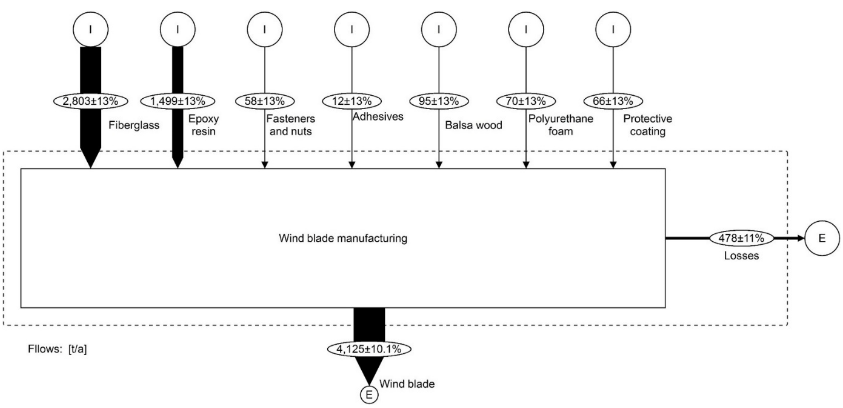

Figure 3. Material flow analysis of wind farm blades (offshore model). The flows are classified as import (I) or export (E).

Table 3. Contribution of water consumption of blades for onshore and offshore wind farms.

Parameter	Onshore		Offshore	
	m^3		m^3	
Fiberglass fabric	627 804	72.08%	584 231	80.07%
Epoxy resin	76 677	8.80%	71 338	9.78%
Metal fasteners and nuts	1 575	0.18%	1 474	0.20%
Adhesives	70	0.01%	64	0.01%
Balsa wood	353	0.04%	329	0.05%
Polyurethane foam	9 078	1.04%	8 473	1.16%
Protective coating (paint)	9 226	1.06%	8 576	1.18%
Energy, diesel	625	0.07%	208	0.03%
Energy, gasoline	27	0.00%	9	0.00%
Energy, ethanol	51	0.01%	20	0.00%
Energy, LPG	68	0.01%	23	0.00%
Energy, electricity	134 705	15.47%	44 895	6.15%
Transportation, truck	10 675	1.23%	9 934	1.36%
Transportation, ship	32	0.00%	30	0.00%
Landfill	7	0.00%	6	0.00%

For both the onshore and offshore models, the energy consumption of wind turbine blades was similar, accounting for biomass, fossil, geothermal, nuclear, primary forest, solar, water, and wind contributions (Figure 4). For the onshore model, the wind turbine blades consumed 704 045 GJ of energy. Energy consumption for the offshore model was 629 815 GJ. Table 4 shows how much energy is consumed by each foreground inventory flow in relation to the wind turbine blade production.

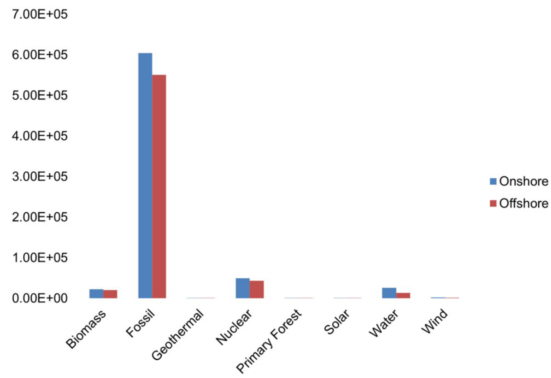

Figure 4. Energy consumption of blades for onshore and offshore wind farms by source in GJ.

Table 4. Contribution of energy consumption of blades for onshore and offshore wind farms.

Parameter	Onshore		Offshore	
	GJ		GJ	
Fiberglass fabric	432 191	61.39%	400 788	63.64%
Epoxy resin	130 351	18.51%	120 386	19.11%
Metal fasteners and nuts	4 039	0.57%	3 758	0.60%
Adhesives	676	0.10%	625	0.10%
Balsa wood	15 299	2.17%	14 259	2.26%
Polyurethane foam	7 910	1.12%	7 378	1.17%
Protective coating (paint)	9 250	1.31%	8 575	1.36%
Energy, diesel	1 934	0.27%	642	0.10%
Energy, gasoline	271	0.04%	90	0.01%
Energy, ethanol	18	0.00%	7	0.00%
Energy, LPG	632	0.09%	211	0.03%
Energy, electricity	35 323	5.02%	11 595	1.84%
Transportation, truck	65 781	9.34%	61 157	9.71%
Transportation, ship	326	0.05%	304	0.05%
Landfill	44	0.01%	41	0.01%

GJ = Gigajoule.

Table 5 presents the contribution of the manufacture of wind turbine blades to GHG emissions, broken down into foreground inventory flows.

Table 5. Carbon footprint of blades for onshore and offshore wind farms.

Parameter	Onshore		Offshore	
	kg CO_2eq		kg CO_2eq	
Fiberglass fabric	26 958 800	66.95%	25 087 200	68.71%
Epoxy resin	6 335 790	15.73%	5 894 590	16.14%
Metal fasteners and nuts	300 043	0.75%	280 649	0.77%
Adhesives	6 195	0.02%	5 718	0.02%

Table 5. Continued…

Parameter	Onshore		Offshore	
	kg CO_2eq		kg CO_2eq	
Balsa wood	62 928	0.16%	58 601	0.16%
Polyurethane foam	394 106	0.98%	367 830	1.01%
Protective coating (paint)	584 012	1.45%	542 825	1.49%
Energy, diesel	138 910	0.34%	46 212	0.13%
Energy, gasoline	17 549	0.04%	5 849	0.02%
Energy, ethanol	453	0.00%	180	0.00%
Energy, LPG	46 721	0.12%	15 602	0.04%
Energy, electricity	1 403 890	3.49%	467 593	1.28%
Transportation, truck	3 995 540	9.92%	3 718 410	10.18%
Transportation, ship	21 083	0.05%	19 639	0.05%
Landfill	2 826	0.01%	2 628	0.01%

3.2 Sensitivity analysis

3.2.1 Influence of capacity factor and lifetime

Figure 5 shows the energy and environmental performance of the manufacture of wind turbine blades per GJ of electricity to be generated over the life cycle of onshore and offshore wind farms.

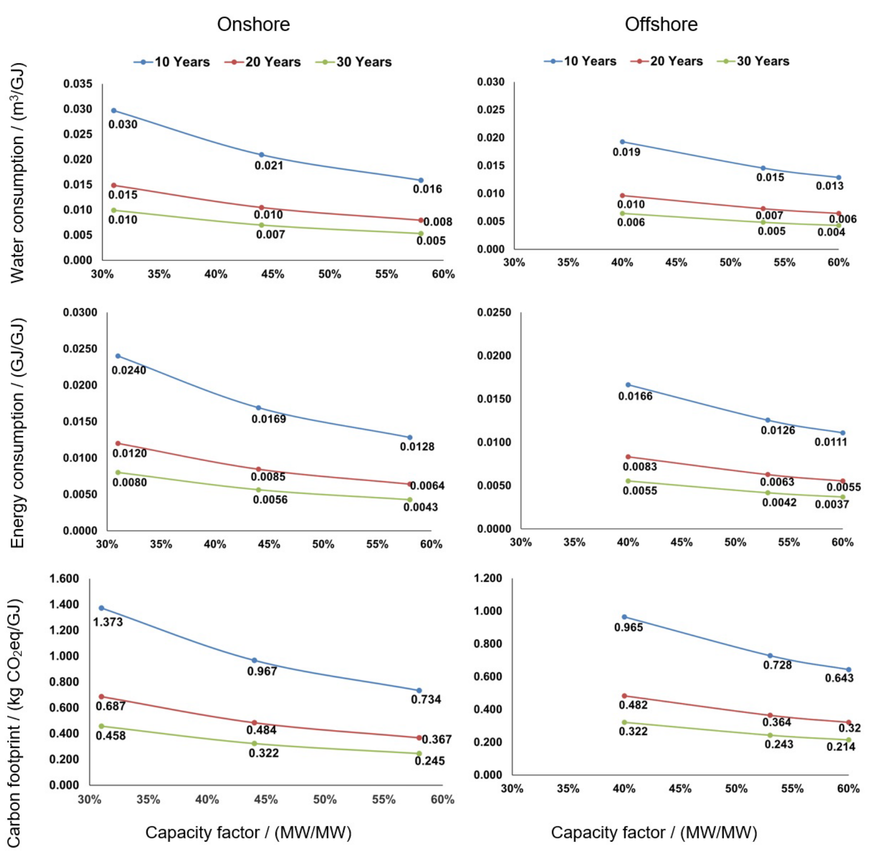

Figure 5. Energy and environmental performance of blades for onshore and offshore wind farms per electricity to be produced under different capacity factor and lifetime scenarios.

Compared to the least favorable scenario and the base scenario, which represents the historical average, the most favorable scenario for the onshore model shows a reduction of 83% in water consumption, 82% in energy consumption, and 82% in carbon footprint. In turn, the most favorable scenario for the offshore model presents a reduction of 79% in water consumption, 78% in energy consumption, and 78% in carbon footprint.

3.2.2 Substitute input for fiberglass fabric

When analyzing the life cycle of wind turbine blades, fiberglass contributed the most to water consumption (72% for onshore and 80% for offshore), energy consumption (61% for onshore and 64% for offshore), and the carbon footprint (67% for onshore and 69% for offshore). As a result, unirrigated jute fiber was used as a substitute input for fiberglass fabric in the evaluation of the energy and environmental performance of the manufacture of wind turbine blades. This reduced water consumption by 38% (onshore) and 42% (offshore), energy consumption by 18% (onshore and offshore), and the carbon footprint by 24% (onshore) and 25% (offshore) (Table 6).

Table 6. Performance of the manufacture of wind turbine blades with fiberglass and jute fiber grown without irrigation in the evaluated categories.

Parameter	Blade model	Fiberglass (base scenario)	Unirrigated jute fiber	Δ
Total water consumption (m^3)	Onshore	870 973	540 511	–38%
Water catchment (m^3)	Onshore	98 149 200 ± 6%	121 114 000 ± 10%	
Return of the water to the water body (m^3)	Onshore	–97 278 200 ± 7%	–120 573 000 ± 12%	
Total water consumption (m^3)	Offshore	729 610	422 072	–42%
Water catchment (m^3)	Offshore	70 399 100 ± 8%	91 767 400 ± 11%	
Return of the water to the water body (m^3)	Offshore	–69 669 500 ± 10%	–91 345 300 ± 12%	
Energy consumption (GJ)	Onshore	704 045 ± 13%	580 406 ± 15%	–18%
Energy consumption (GJ)	Offshore	629 815 ± 12%	513 455 ± 15%	–18%
Carbon footprint (kg CO_2eq)	Onshore	40 268 846 ± 12%	30 480 400 ± 15%	–24%
Carbon footprint (kg CO_2eq)	Offshore	36 513 526 ± 12%	27 403 700 ± 14%	–25%

4 Discussion

Compared to the offshore model, onshore wind farms required three times as many wind turbine blades. However, the amount of waste generated in this model was 7.5% greater. Figures 2 and 3 suggest that even before the business is operational, the construction of a wind farm generates a significant amount of waste composite materials. In total, 500 t of composite materials would be generated for the evaluated scenarios in this study and these materials need to be properly treated. In a technical note, the Brazilian Ministry of Mines and Energy highlights the importance of measures to maintain, upgrade, or decommission wind farms to reduce their negative environmental effects once they have already served their purpose (EPE, 2021). However, the document does not mention the amount of waste material generated during manufacturing that is impregnated with epoxy resin and fiberglass, and this issue should be treated in an environmentally responsible way.

Regarding manufacturing waste materials, the Caucaia West Metropolitan Sanitary Landfill (ASMOC – Aterro Sanitário Municipal Oeste de Caucaia) serves industries in the Pecém Industrial and Port Complex (CIPP) and is located 50 km away from the complex. Non-hazardous industrial solid waste is disposed in this landfill by the CIPP (Silva et al., 2017). When Giannetti et al. (2012) analyzed the operation of a manufacturer of wind turbine blades in Sorocaba, São Paulo, they found that 10% to 15% of waste composite materials are disposed in the Sorocaba inert landfill. Similarly, Papadakis et al. (2010) reinforce that the waste generated in the manufacture of each wind turbine blade represents 10% of the mass of resin and fiber due to the cutting process of the resin-impregnated fiberglass materials. However, some countries in Europe have banned the use of landfills for this purpose. Law No. 1999/31/EC prohibits the landfilling of untreated fiber-reinforced polymer waste, stating that only biologically stabilized waste with low organic content may be landfilled (Kimm et al., 2020). Due to their high organic content, Germany, for instance, banned the disposal of glass-fiber reinforced plastics in landfills in June 2005 (Larsen, 2009).

To dispose the composite materials waste in an environmental way, companies should change their business models. NEOCOMP is a licensed company located in Bremen, Germany, that recycles and uses fiber reinforced plastics (FRP) to create solid recovered fuel (SRF). FRPs are collected, cut, crushed, and mixed with other materials. In the cement factory, they are used in the cement kiln (Nagle et al., 2020). The FRP is burned in a cement kiln which minimizes the need for coal or natural gas as a fuel and reduces carbon dioxide emissions by up to 16%. The leftover fiberglass is then combined with clay and limestone to make cement (EPRI, 2020). Therefore, the 500 t of waste generated during the manufacture of the wind blades should be reduced at the source by cleaner production, and when inputs are wasted, they should be used in a higher added value way than simply being landfilled, for example, as a raw material for other processes such as cement manufacturing.

Most of the energy needed in the manufacture of wind turbine blades comes from non-renewable sources, with fossil fuels accounting for 86%, nuclear energy for 7%, and other sources for 7% (Figure 4). This outcome is similar to the study by Gomaa et al. (2019), which shows that large companies continue to rely primarily on fossil fuels for their energy needs.

Figure 5 suggests that increasing the capacity factor and lifetime of wind turbine blades reduces the amount of water, energy, and carbon dioxide (CO_2) used in the production of each GJ of electricity to be produced in the wind farm. The scenario with the lowest carbon footprint (0.214 kg CO_2eq/GJ) represents an offshore wind farm with a capacity factor of 60% MW/MW and a lifetime of 30 years. The least desirable scenario, on the other hand, represents the onshore model with a capacity factor of 31% MW/MW and a lifetime of 10 years (1.373 kg CO_2eq/GJ). The most advantageous scenario shows a reduction of 84% in the carbon footprint when comparing these two scenarios. While Ahmad et al. (2021) point that power companies use drones to inspect blades in a safer and less expensive way, Yang et al. (2012) suggest the use of videometry to assess the structural behavior of wind turbine blades on a large scale during the operation phase. The capacity factor is influenced by the site selection for the wind farm and depends on the availability of transmission lines to connect the energy produced to the National Interconnected System (SIN – Sistema Interligado Nacional), showing that government investments are needed to upgrade and build Brazilian power transmission systems (Diógenes et al., 2019; Herrera et al., 2019; Köberle et al., 2018). The use of artificial intelligence (AI) supports real-time communication with wind farms regarding changes in wind direction and speed along with the status of the transmission grid. Thus, utilities can make the shutdown and startup of rotating parts more efficient, prevent unscheduled outages, and predict future maintenance needs based on the asset performance (Ahmad et al., 2021).

Jute fiber grown without irrigation can replace fiberglass supporting to reduce water consumption, energy consumption, and carbon footprint (Table 6). Plant fibers are less expensive, readily available, mechanically suitable, and impact-resistant materials that come from renewable resources (Silva Fo. et al., 2015). They have gained popularity as a reinforcing material for FRPs due to their favorable mechanical qualities, high specific strength, non-abrasive nature, and low cost (Thomas & Ramachandra, 2018). Summerscales (2021) states that the use of plant fibers extracted from plant stems as more environmentally friendly composite materials has increased.

In a literature review, we found studies that evaluated the use of various plant fibers to substitute fiberglass in wind turbine blades (Table 7).

Table 7. Summary of the types of plant fibers used to replace fiberglass in wind turbine blades found in the consulted literature review.

Study	Country	Plant fiber in a polymer composite	Results
Holmes et al. (2009)	Denmark	Hot-pressed bamboo and poplar wood	· The manufacture of hot-pressed bamboo and poplar wood-based laminates for wind turbine blade applications is feasible.
Boopalan et al. (2012)	India	Jute and sisal	· The mechanical properties of the jute fiber-reinforced composite were higher compared to the sisal fiber-reinforced composite;
			· The sisal fiber absorbs more water than the jute fiber, decreasing mechanical properties;
			· When comparing tensile strength, sodium hydroxide treated jute composites showed better results than sodium hydroxide-treated sisal composites.
Shah et al. (2013)	United Kingdom	Linen and polyester	· The linen fiber and polyester composite is 10% lighter than that of fiberglass and polyester due to the lower density of the plant fibers;
			· The linen fiber meets the design and structural integrity requirements, according to certification standards, for an 11 kW turbine.
Praciano et al. (2014)	Brazil	Carnauba	· The mechanical properties of carnauba have the required characteristics for the manufacture of wind turbine blades.
Silva Fo. et al. (2015)	Brazil	Piassava	· The piassava fiber addition significantly improved the impact strength of the composite compared to the composite without the piassava reinforcement.
Banga et al. (2015)	India	Bamboo	· The tensile, flexural and impact strength, and hardness of bamboo fiber-reinforced epoxy composites were higher compared to epoxy composites without bamboo reinforcement;
			· The water absorption of the bamboo-based composites saturates after a 40-day exposure with little effect of water on the composite.
Bakri et al. (2016)	Indonesia	Coconut	· The mechanical properties of tensile, impact, shear, flexural, and compressive strength were similar to the properties of wood, but lower than the properties of fiberglass composites for application in small wind turbine blades.
Widiastuti (2016)	Indonesia	Bamboo	· This renewable material is a candidate for application in wind turbine blades, considering its favorable mechanical properties, simplicity of processing, and biodegradable properties.
Wang et al. (2019b)	China	Jute	· The study evaluated the effects of hot alkaline chemical treatment with different NaOH mass concentrations (2%, 4%, 6%, 8%, and 10%) on the mechanical properties of jute/epoxy composites;
			· The alkali treatment directly affects the properties of the jute fiber, which removes non-cellulosic materials and makes the fiber better able to rearrange itself along the fiber direction, and improves the adhesion of the fiber matrix;
			· Composites with 6% NaOH-treated jute fabric had the best result. Their tensile strength, flexural strength, modulus of elasticity, and flexural modulus improved by 37%, 72%, 23%, and 72%, respectively, compared with composites reinforced with untreated fabrics.

Table 7. Continued…

Study	Country	Plant fiber in a polymer composite	Results
Müssig et al. (2020)	Germany	Hemp	· Selection should be based on crop variety, to achieve a more consistent fiber quality;
			· Further developing product design using hemp biocomposites as structural components, for example, for wind turbine blades, and evaluating structural properties at multiple scales is needed to support the use of hemp composites on an industrial scale.
Karim et al. (2021)	United Kingdom	Jute	· When the jute fibers were coated in graphene and then used in composites, Young's modulus (a mechanical property that measures the stiffness of solid materials) increased from 30 GPa (jute composite without graphene coating) to 78 GPa, achieving a value 18% higher than S-glass (composite of silicon, aluminum, and magnesium oxides) and 40% higher than E-glass (composite of silicon, aluminum, calcium, magnesium, and boron oxides);
			· The graphite-coated jute fiber performs mechanically better and is environmentally advantageous to the synthetic glass fiber due to its potential for carbon capture and storage.
Nurazzi et al. (2021)	Malaysia	Jute	· Jute fiber hybrid composites have been widely used in various structural and engineering applications: aeronautical, marine, construction, automotive, and sporting goods;
			· Regarding stiffness and cost, plant fiber polymer composites are becoming increasingly competitive with other synthetic polymer composites. Tensile and impact strength values are approaching those of synthetic composites.

The findings in the consulted literature show many plant fiber alternatives to the fiberglass fabric currently used in wind turbine blades. The performance of wind turbine blades in terms of energy and the environment tends to benefit from the replacement of this input. Moreover, this replacement simplifies the recycling of the composite material produced during and after the lifetime of wind turbine blades, since besides being biodegradable, plant fiber-reinforced composites can be milled, reimpregnated, and reused at the end of their lifetime (Dorigato, 2021). Brazil is abundant in all the plant-based materials mentioned in this section. For instance, bamboo is one of the fastest growing plants over a short period of time and is readily available in most tropical nations (Rassiah et al., 2014). On the other hand, plant fibers are sensitive to water, thus, the matrix polymer would provide long-term protection if these composites were used instead of fiberglass. They are also acceptable for the marine environment, as is the case for offshore application. Initial research with conventional marine thermoset matrix polymers suggests the possibility of creating a robust composite for marine applications (Davies et al., 2022). Therefore, investing in the development of a highly weather-resistant plant fiber suitable for use in wind turbine blades will allow Brazil to become a leader in the production of this type of product and reduce dependence on foreign inputs in a booming market in the country.

The evaluation of plant fiber research in the consulted literature (Table 7) was restricted to laboratory tests, prototypes, or small-scale turbine manufacturing. To meet the need for turbines in a wind farm, as is the case in this study, the implementation of wind turbine blades made of plant fibers on a commercial and industrial scale is necessary.

Regarding transportation, this study assumed that the materials were transported via the highway network from the Port of Santos to the manufacturer of wind turbine blades. Although the Port of Pecém is close to the manufacturing facility, the flow of ships between these ports is more expensive and less frequent. However, the quantity and quality of cabotage transport in Brazil is expected to increase and improve respectively, therefore, the logistics costs of using the maritime modal may become more beneficial after the approval of Law No. 14.301 (Brasil, 2022). Consequently, the energy consumption associated with the transportation of raw materials needed to produce wind turbine blades may greatly reduce.

Society benefits from the growth of wind energy in many ways, including greater energy security, a more diverse power grid, and less dependance on imported fossil fuels. Thus, incentives for the spread of the exploration and use of fossil fuels (oil, gas, and coal) should be removed and investment resources redirected from these sectors to increase the production and use of renewable sources (Grupo de Trabalho da Sociedade Civil para a Agenda 2030, 2021) and expand wind energy. These actions contribute to achieve the sustainable development goals of the 2030 Agenda (UNDP, 2022).

5 Conclusion

In order to build onshore and offshore wind farms with a nominal capacity of 300 MW, we evaluated the life cycle of the production of two types of wind turbine blades. The production of wind turbine blades results in a considerable amount of composite waste (around 500 t in this study). In Brazil, this material is usually disposed in landfills for industrial waste. However, this study showed that more advantageous approaches have been used to enable this waste to be disposed in an environmentally responsible way.

Most (93%) of the energy used in the entire life cycle of wind turbine blades comes from non-renewable sources. Fiberglass fabric influences water consumption (72% onshore and 80% offshore), energy consumption (61% onshore and 64% offshore), and the carbon footprint (67% onshore and 69% offshore) more than the other inputs. Moreover, the effect of road transport is significantly greater compared to sea transport. Even though the contribution of transportation was up to 10% in the categories analyzed, producing inputs near the manufacturing facility evaluated in this study supports the reduction of water consumption, energy consumption, and the carbon footprint of transportation.

According to the results of the sensitivity analysis, improving the capacity factors of wind farms and the lifetime of wind turbine blades should take precedence to reduce water consumption, energy consumption, and the carbon footprint per unit of electricity produced. Thus, government investments are needed to modernize and decongest the national power grid. Wind farms owners can extend the lifetime of their components by doing predictive and preventive maintenance on the wind turbine blades using sensors and drones. Manufacturers should highlight the importance of creating reliable wind turbine blades with high structural strength to withstand the fatigue cycles that the components undergo over their lifetime.

Jute fiber grown without irrigation had a lower water consumption, energy consumption, and carbon footprint than fiberglass when used as a substitute. Brazilian renewable resources can provide many plant fiber alternatives, including jute, bamboo, coconut, carnauba, and piassava. However, we found neither a wind farm using blades made of plant fibers nor a manufacturer producing them on a commercial scale. Thus, the possibility of creating a new product from a renewable, recyclable, and abundant source in Brazil that is more sustainable than most is great due to the advantages of this solution for the environment. However, to meet the demand of wind farms, further research is needed to assess the technological and financial viability of using plant fibers on an industrial scale.

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Authors contribution

Mário Joel Ramos Júnior participated in the conception and development, literature survey, data collection, article writing and standardization of the norms according to the journal. Diego Lima Medeiros participated in the planning of the study, methodological design, guided the collection and treatment of the data obtained and revision of the article. Edna dos Santos Almeida participated in the methodological design, analysis and interpretation of the data obtained and final review of the article.

Appendix 1. The basic uncertainty and pedigree score.

Table A1. Basic uncertainty and pedigree score of inventory flows.

Material	Basic uncertainty in GSD²*	Pedigree score [Pedigree uncertainty in GSD²] a	Name in openLCA® 1.11.0
Input			
Fiberglass fabric [b]	1.05	4,2,2,1,3 [1.20;1.02;1.03;1.00;1.20]	*glass fibre reinforced plastic production, polyamide, injection moulded | glass fibre reinforced plastic, polyamide, injection moulded | Cutoff, U - RoW*
Epoxy resin	1.05	4,2,2,1,3 [1.20;1.02;1.03;1.00;1.20]	*epoxy resin production | epoxy resin | Cutoff, U – RoW*
Metal fasteners and nuts	1.05	4,2,2,1,3 [1.20;1.02;1.03;1.00;1.20]	*steel production, chromium steel 18/8, hot rolled | steel, chromium steel 18*
Adhesives	1.05	4,2,2,1,3 [1.20;1.02;1.03;1.00;1.20]	*bitumen adhesive compound production, hot | bitumen adhesive compound, hot | Cutoff, U - RoW*
Balsa wood	1.05	4,2,2,1,3 [1.20;1.02;1.03;1.00;1.20]	*beam, hardwood, raw, kiln drying to u=10% | sawnwood, beam, hardwood, raw, dried (u=10%) | Cutoff, U - RoW*
Polyurethane foam	1.05	4,2,2,1,3 [1.20;1.02;1.03;1.00;1.20]	*polyurethane production, flexible foam | polyurethane, flexible foam | Cutoff, U - RoW*
Protective coating (paint)	1.05	4,2,2,1,3 [1.20;1.02;1.03;1.00;1.20]	*coating powder production | coating powder | Cutoff, U - RoW*
Energy, diesel	1.05	1,4,1,1,1 [1.00; 1.10; 1.00; 1.00; 1.00]	*market for diesel, burned in agricultural machinery | diesel, burned in agricultural machinery | Cutoff, U - GLO*
Energy, gasoline	1.05	1,4,1,1,1 [1.00; 1.10; 1.00; 1.00; 1.00]	*market for petrol, unleaded, burned in machinery | petrol, unleaded, burned in machinery | Cutoff, U - GLO*
Energy, LPG	1.05	1,4,1,1,1 [1.00; 1.10; 1.00; 1.00; 1.00]	*heat production, propane, at industrial furnace >100kW | heat, district or industrial, other than natural gas | Cutoff, U - RoW*
Energy, ethanol [c]	1.05	1,4,1,1,1 [1.00; 1.10; 1.00; 1.00; 1.00]	*ethanol production from sugarcane | ethanol, without water, in 95% solution state, from fermentation | Cutoff, U – BR; treatment of bagasse, from sugarcane, in heat and power co-generation unit, 6400kW thermal | heat, district or industrial, other than natural gas | Cutoff, U – GLO (without the fuel bagasse, from sugarcane)*
Energy, electricity	1.05	1,4,1,1,1 [1.00; 1.10; 1.00; 1.00; 1.00]	*market for electricity, low voltage | electricity, low voltage | Cutoff, U - BR*
Transportation, truck	2.00	3,4,1,5,2 [1.10;1.10;1.00;1.10;1.05]	*market for transport, freight, lorry, unspecified | transport, freight, lorry, unspecified | Cutoff, U - GLO*
Transportation, ship	2.00	3,4,1,5,2 [1.10;1.10;1.00;1.10;1.05]	*market for transport, freight, sea, transoceanic ship | transport, freight, sea, transoceanic ship | Cutoff, U - GLO*
Output			
Losses (fiberglass and epoxy-impregnated material)	1.05	4,3,3,1,2 [1.20;1.05;1.10;1.00;1.05]	*market for inert waste, for final disposal | inert waste, for final disposal | Cutoff, U - RoW*

RoW: Rest of World. GLO: Global. *GSD²: relative squared geometric standard deviation. [a]Pedigree matrix indicators: source reliability, completeness, temporal correlation, geographic correlation, and technology correlation, respectively. The inventory database was used (ecoinvent_case_studies_Ceramic_cup_vs_Paper_cup) with a method database (openLCA_LCIA_pack_2_1_3). [b]*Textile production, jute* | *textile, jute* | *Cutoff, U – RoW* was considered in the sensitivity analysis of the replacement of fiberglass by jute fiber grown without irrigation. [c]For ethanol, the combination of two supplier inventories was considered: one representing the production of 0.0007 t of the fuel and the other representing the burning of 0.02 GJ of the fuel per blade.

Equation A1 (Rosenbaum et al., 2018) combined the basic uncertainty and the pedigree uncertainties of each inventory flow:

$$GSD_X^2 := e^{\sqrt{\sum_{i=1}^{n}\left[ln\left(GSD_{Xi}^2\right)\right]^2}} \quad \text{(A1)}$$

Equation A2 converted GSD^2, representing a 95.45% confidence interval, into GSD, representing a 68% confidence interval:

$$GSD_X := \sqrt{GSD_X^2} \quad \text{(A2)}$$

Equation A3 (Ciroth et al., 2012) converted the combined uncertainty of each inventory flow into relative arithmetic standard deviation, or coefficient of variation (CV):

$$CV_X := \sqrt{e^{(ln(GSD_X)^2)} - 1} \quad \text{(A3)}$$