WIND TURBINE BLADE MANUFACTURING: A MATERIAL FLOW ANALYSIS

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Abstract: This study aims to analyze the material flow of wind turbine blade manufacturing for an onshore wind farm with a nominal capacity of 300 Megawatts (MW). For this purpose, the Material Flow Analysis (MFA) method was used in STAN® 2.7.101 software. A material demand of 4,946 t of material and waste generation of 514 t from composite material made of fiberglass and epoxy resin were estimated in the manufacturing of 225 wind turbine blades in one year. In this way, cleaner production practices are required to promote the reduction of material loss and the utilization of waste materials.

Keywords: Renewable energy; Wind energy; Wind turbine blade; Waste generation; Composite material.

FABRICAÇÃO DE PÁS DE TURBINA EÓLICA: UMA ANÁLISE DE FLUXO DE MATERIAL

Resumo: Este estudo tem como objetivo analisar o fluxo de material da fabricação de pás de turbina eólica para um parque eólico *onshore* com capacidade nominal de 300 Megawatts (MW). Para tal, foi utilizado o método de Análise de Fluxo de Material (AFM) no software STAN® 2.7.101. Foi estimada uma demanda de 4,946 t de material e geração de 514 t de resíduos de material compósito de fibra de vidro e resina epóxi na fabricação de 225 pás de turbina eólica em um ano. Desta forma, práticas de produção mais limpa são requeridas para promover a redução de perda de material e o aproveitamento de materiais residuais.

Palavras-chave: Energia renovável; Energia eólica; Pá de turbina eólica; Geração de resíduo; Material compósito.

1. INTRODUCTION

The world's electricity matrix was made up of 73% from non-renewable sources and 27% from renewable sources in 2019 [1]. The predominant system of electricity production uses coal, oil and natural gas as fuel. These fuels are made up of hydrocarbons that emit CO_2, among other gases, during combustion. Such emissions are harmful to the population health and environment quality. Wind energy is a clean source and one of the fastest growing electricity markets in the world, with an average expansion rate of 20% per year for installed capacity between 2001 and 2021 [2,3]. In Brazil, the installed capacity for electricity production from wind power has expanded considerably in recent years. According to ABEEÓLICA [4], such capacity increased from 928 MW in 2010 to 17,750 MW in 2020, which represents an average expansion rate of 34% per year.

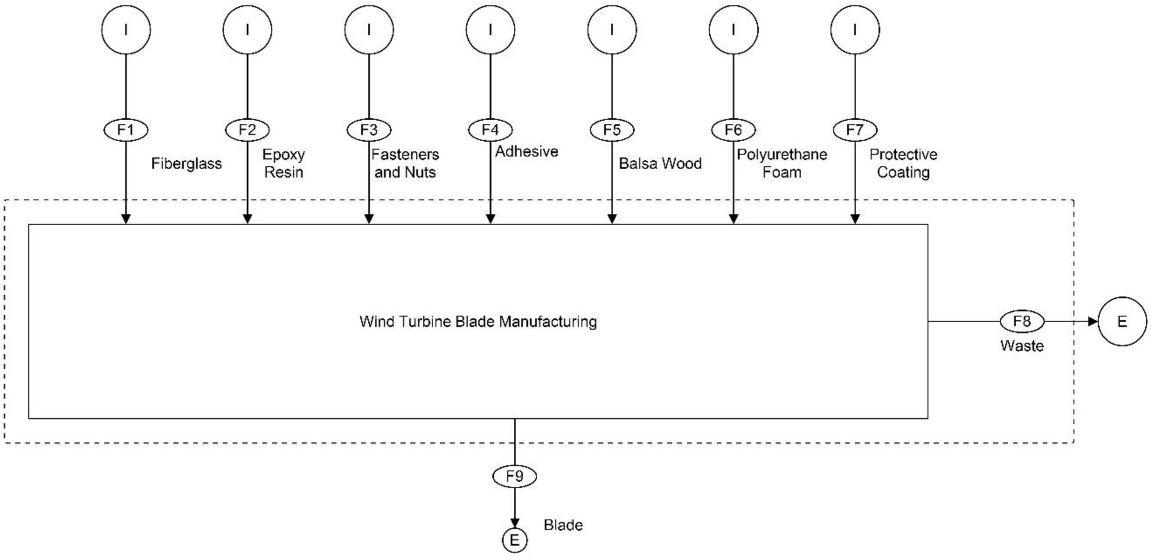
Most wind turbine components are recycled after decommissioning of the wind farm, except for wind turbine blades (also called as blades in this paper) which are made of composite material and usually contain a high proportion (60 - 70% in mass basis w/w) of glass fiber reinforced polymer (GFRP) or carbon fiber reinforced polymer (CFRP) [5,6]. Such characteristic makes their fate subject of environmental concern [7], mainly due to the waste generation increase after the blades' useful life. In this regard, a great attention has been given to fiber reinforced polymer (FRP) blade recycling from mechanical and thermochemical processes [8]. However, blade disposal in landfill or incineration have been the most common treatment method for its end of life [9]. These two solutions are in the two lowest levels of the Brazilian National Solid Waste Policy guidelines [10] and of the waste management priorities list of the European Commission needed to promote the circular economy [11]. The aforementioned studies identified the increased use of composite materials due to the expansion of the wind industry and the chosen options for disposal of blade waste in the end of life, despite of the lack for propositions to reduce waste generation at the source. In this context, the objective of this paper is to analyze the material flow of wind turbine blade manufacturing for an onshore wind farm with a nominal capacity of 300 Megawatts (MW).

2. METHODOLOGY

The Material Flow Analysis (MFA) method [12] was considered in this study to evaluate the manufacturing of wind turbine blades, which are produced in fiberglass and epoxy resin composite material in a factory located at the Pecém Port and Industrial Complex (CIPP) in Caucaia, Ceará, Brazil. The annual production of the factory was considered to be the quantity of blades required to build a wind farm with a nominal capacity of 300 MW. The wind turbine blades capture the wind kinetic energy of the wind and convert it into mechanical energy. The nominal unitary capacity of each wind turbine is 4 MW, so 225 wind turbine blades are required for 75 wind turbines, which in this study were of the model MySE4.0-145 produced by Mingyang Defeng Energy Systems Co. Ltd. The rotor diameter is 145 m and the rotor area is 16,505 m², while a single blade nominal weight is 20,227 t and each wind turbine is equipped with 3 rotor blades [13].

The software STAN® 2.7.101 (short for subSTance flow ANalysis) was used in this study, which is a free software used in AFM according to the Austrian standard ÖNorm S 2096 [14]. Figure 1 shows the product system evaluated in this study.

Figure 1. Product system of wind turbine blade manufacturing. Abbreviations: flows (F), imports (I), and exports (E).



The wind turbine blade structure evaluated in this study consists of fiberglass textile, epoxy resin, metal fasteners and nuts, adhesives, balsa wood, polyurethane foam and protective coating (paint) [15]. Table 1 shows the proportion of materials in a wind blade based on Liu and Barlow [16]. During the manufacturing process, the fiberglass textile is impregnated with epoxy resin in a liquid state which is changed to a solid state in the curing reaction [17]. The mass balance of a blade manufacturing is presented in Table 1. The relative arithmetic standard deviation of the mean of each inventory flow was estimated from the basic and pedigree uncertainties [18], which are presented in Table A1 of the Appendix.

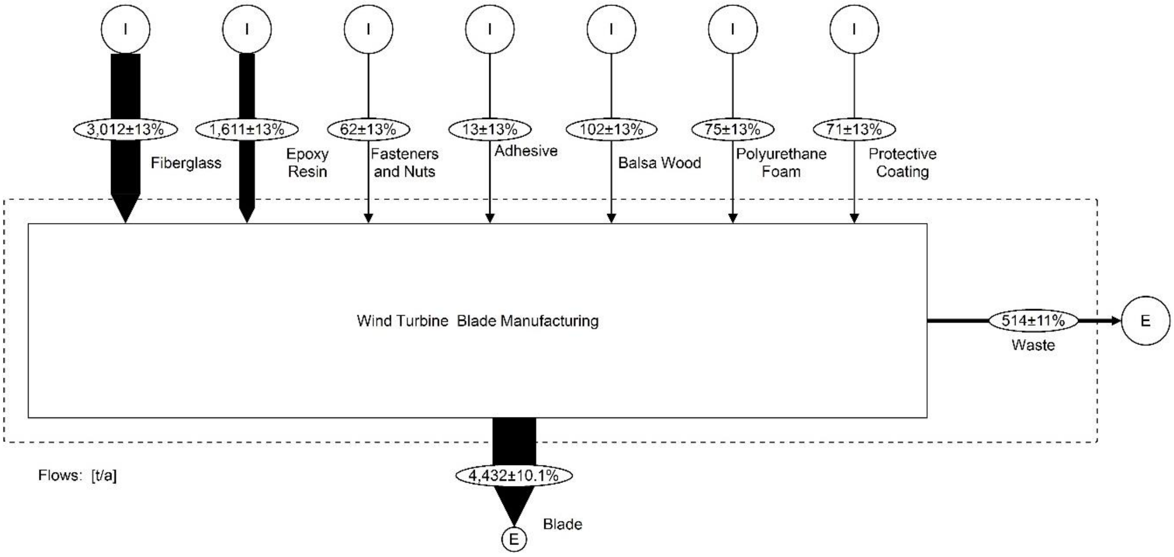
Table 1. Mass balance of the manufacturing of an onshore wind turbine blade.

Parameter	**Unit**	**Blade**	**Contribution**	**Source**
Input				
Fiberglass textile	t	13.386 ± 13%	60.4%	[16]
Epoxy resin	t	7.155 ± 13%	32.3%	[16]
Metal fasteners and nuts	t	0.276 ± 13%	1.4%	[16]
Adhesive	t	0.590 ± 13%	0.3%	[16]
Balsa wood	t	0.453 ± 13%	2.3%	[16]
Polyurethane foam	t	0.335 ± 13%	1.7%	[16]
Protective Coating (paint)	t	0.315 ± 13%	1.6%	[16]
Output				
Blade	t	20.227 ± 10.1%	90%	
Losses (with fiberglass textile and epoxy resin impregnated material)	t	2.283 ± 11%	10%	[17,19]

3. RESULTS AND DISCUSSION

The mass balance of the MFA for blade manufacturing of a wind farm with a 300 MW nominal capacity after data reconciliation is presented in Figure 2.

Figure 2. Material flow analysis for 225-blade manufacturing of the onshore wind farm of this study.



The results in Figure 2 show that a wind farm generates a large amount of composite material of the turbine blade manufacturing even before its operation. For the characteristics evaluated in this study, 514 t of composite material waste are generated which require adequate treatment. A Technical Note issued by the Brazilian Ministry of Mines and Energy highlights that actions for maintenance, modernization, and decommissioning, should be taken to mitigate the environmental impacts of wind farms at their life [7]. However, such document has no recommendation for waste management of materials such as epoxy resin and fiberglass composite losses generated in the blade manufacturing.

Giannetti et al. [17], when evaluating the manufacturing of a wind turbine blade factory in Sorocaba (São Paulo), identified that 10-15% of the inputs are lost in the form of waste which are landfilled. Papadakis et al. reinforce that wind turbine blade manufacturing losses are generated in the composite material cutting [19]. European countries have banned the disposal of FRP waste in landfills according to the Law 1999/31/EC and only biologically stabilized waste with low organic content can be landfilled [20]. For instance, Germany, banned the disposal of GRFP in landfills in June 2005 due to its high organic content [21].

Waste management companies are adapting their business model to provide an environmentally adequate destination for composite material waste. Neocomp is a certified waste treatment company, located in Bremen, Germany, that reprocesses and utilizes GFRP. The GFRP is collected, cut, crushed, and combined with other materials to form a solid recovered fuel (SRF). The SRF is shipped to a cement plant which is burned in a cement kiln, where the energy recovered from the polymer resins eliminates the use of coal or natural gas and reduces the carbon dioxide emissions by up to 16% [22]. Then, the residual fiberglass is incorporated into the cement in combination with limestone and clay or shale [23]. Therefore, the 514 t generated waste in the wind turbine blade manufacturing estimated in this study should be reduced at the generating source with a cleaner production and, when the inputs are lost in the form of waste, these should have an improved destination than the simple disposal in landfills, i. e. serving as input for other processes.

4. CONCLUSION

The material flow of the wind turbine blade manufacturing for an onshore wind farm with a nominal capacity of 300 Megawatts (MW) was analyzed. The blade mass was estimated at 20,227 t, while the material loss manufacturing was estimated at 2,283 t. Thus, the production of 225 blades for a wind farm generates 514 t of composite material. The predominant destination for these residual materials in Brazil has been industrial landfills. However, solutions for material and energy recovery that are being practiced, which enables an environmentally appropriate disposal of such materials were discussed. Moreover, further studies are required to evaluate the energy and environmental performance of wind turbine manufacturing for wind farms.

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APPENDIX

Table A1. Basic uncertainty and pedigree uncertainty of the inventoried flows.

Parameter	Basic uncertainty in GSD^2	Uncertainty pedigree in GSD^2 [Pedigree Score][a]
Input		
Fiberglass textile	1.05	1.20; 1.02; 1.03; 1.00; 1.20 [4,2,2,1,3]
Epoxy resin	1.05	1.20; 1.02; 1.03; 1.00; 1.20 [4,2,2,1,3]
Metal fasteners and nuts	1.05	1.20; 1.02; 1.03; 1.00; 1.20 [4,2,2,1,3]
Adhesive	1.05	1.20; 1.02; 1.03; 1.00; 1.20 [4,2,2,1,3]
Balsa wood	1.05	1.20; 1.02; 1.03; 1.00; 1.20 [4,2,2,1,3]
Polyurethane foam	1.05	1.20; 1.02; 1.03; 1.00; 1.20 [4,2,2,1,3]
Protective Coating (paint)	1.05	1.20; 1.02; 1.03; 1.00; 1.20 [4,2,2,1,3]
Output		
Blade[b]		
Losses (with fiberglass textile and epoxy resin impregnated material)	1.05	1.20; 1.05; 1.10; 1.00; 1.05 [4,3,3,1,2]

GSD^2: relative geometric standard deviation squared. [a]Pedigree matrix indicators: reliability, completeness, temporal correlation, geographic correlation, and technology correlation, respectively. [b]Blade relative arithmetic standard deviation was estimated through STAN data reconciliation.

The basic uncertainty and pedigree uncertainty of each inventoried flow were combined from Eq. A.1 [24].

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

The GSD^2, which represents a 95.45% coverage interval (or confidence interval), was converted to GSD to represent a 68% coverage interval from Eq. A.2.

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

The combined uncertainty of each inventoried flow in GSD was converted to relative arithmetic standard deviation, known as coefficient of variation (CV), from Eq. A.3 [25].

$$CV_X := \sqrt{e^{(ln(GSD_X)^2)} - 1} \quad \text{(A.3)}$$