LOGISTICS OPTIMIZATION OF DECOMMISSIONED WIND TURBINE BLADES FOR ENERGY RECOVERY IN A CEMENT PLANT IN BAHIA

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Abstract: This study aims to evaluate the logistics of decommissioning wind turbine blades for an energy recovery scenario in a cement kiln in the State of Bahia – Brazil. The Center of Gravity Method (CGM) was used to define the optimized location of the Materials Processing Center (MPC) from waste resources based on the coordinates, composite material mass and transportation cost of the 247 wind farms, while the Material Flow Analysis (MFA) was used to elaborate the mass balance from Brotas de Macaúbas Wind Complex. The results indicated that the energy recovery of the 1 070 t composite material of the Brotas de Macaúbas Wind Complex can replace 642 t of petroleum coke in a cement plant. Energy recovery in cement plants provides a feasible method for composite disposal of old blades, as long as the costs of transportation, segregation, and shredding are affordable.

Keywords: Locational optimization; Wind turbine blade; Solid waste management; Energy recovery; Composite material.

OTIMIZAÇÃO DA LOGÍSTICA DE PÁS DE TURBINA EÓLICA DESCOMISSIONADAS PARA RECUPERAÇÃO ENERGÉTICA EM UMA CIMENTEIRA NA BAHIA

Resumo: Este estudo objetiva avaliar a logística de descomissionamento de pás de turbina eólica para um cenário de recuperação energética em forno de cimento no Estado da Bahia – Brasil. O Método do Centro de Gravidade (MCG) foi utilizado para definir a localização otimizada do Centro de Processamento de Materiais (CPM) de fontes residuais com base nas coordenadas, massa de material compósito e custo de transporte dos 247 parques eólicos, enquanto a Análise de Fluxo de Material (AFM) foi utilizada para elaborar o balanço de massa do Complexo Eólico Brotas de Macaúbas. Os resultados indicaram que a recuperação energética de 1 070 t de material compósito do Complexo Eólico Brotas de Macaúbas pode substituir 642 t de combustível fóssil em uma cimenteira. A recuperação energética é uma rota promissora para a destinação de compósitos de pás descomissionadas, desde que os custos de transporte, segregação e trituração sejam viáveis.

Palavras-chave: Otimização de localização; Pá de turbina eólica; Gerenciamento de resíduos sólidos; Recuperação de energia; Material composto.

1. INTRODUCTION

The Brazilian context, especially the Northeast of the country, has shown a promising potential for the expansion of wind electricity production. The wind power capacity in Brazil is distributed at 91% in the Northeast region, followed by 8.9% in the South region and 0.1% in the Southeast region in 2022 base year [1]. In 2021, 11% of all electricity generation injected into the National Interconnected System (SIN) came from wind power [2], which reached 20% of the country supply at peak time [3]. The State of Bahia is the national leader in wind power generation in Brazil with 247 wind farms in operation and 6.43 GW of installed capacity in 2022 base year [1]. The Brotas de Macaúbas Wind Complex, which began the commercial operation in 2012, was the first wind power project installed in Bahia [1,4].

Wind farms components are made of materials with high recycling rates, such as the tower, foundation, generator and gearbox including steel, aluminum and copper [5]. On the other hand, wind turbine blades, which are mostly made of glass fiber reinforced polymers (G-FRP), have a low recycling rate due to the types of materials involved and their complex composition [5] which results in a high cost that makes large-scale recycling unfeasible in the short term [6]. Worldwide, landfill is the most common disposal route for polymers and their derived materials. Approximately 90% of the G-FRP is landfilled globally [7]. However, the landfill disposal of large G-FRP pieces is not an option in the European Union and, in the near future, is likely to be banned in more countries due to stricter environmental regulations [8].

The energy recovery of G-FRP through co-processing in cement kilns has been practiced in Europe, which has the advantages of scalability for processing large material quantities with low waste generation. The main advantages of co-processing are the reduction of natural resource extraction and of greenhouse gas emissions, while it contributes to increase the landfills useful life, improve public health and reduce thermal energy costs [9]. Furthermore, it is at the highest technology maturity level (TRL 9), which refers to a proven and implemented technology [10] and is attractive option for G-FRP disposal in the short term.

In Brazil, co-processing of solid waste has been practiced for more than 20 years. In 2021, 2 408 million tonnes of waste materials of various origins were co-processed, which were no longer destined to landfills and replaced fuels used in the cement industry [9]. Co-processing is regulated at the federal level in Brazil by CONAMA 499/2020 [11] and some states have specific complementary legislation. Four cement production units are installed in the State of Bahia, three of which are grinding units and one is an integrated unit with kiln that is licensed by the state environmental agency to co-process waste [9].

This work aims to evaluate the logistics of decommissioning wind turbine blades for an energy recovery scenario in a cement kiln. In this regard, a Materials Processing Center (MPC) from waste sources was proposed for decommissioned wind turbine blades in the State of Bahia, based on the Center of Gravity Method (CGM) for an optimized location, for later co-processing in cement kilns. The Material Flow Analysis (MFA) was used to elaborate the mass balance of the evaluated scenario.

2. METHODOLOGY

The follow methodological procedure was conducted in this study: the identification of wind farms in operation (Step 1) was made by consulting the

Generation Information System (SIGA) of the National Electric Energy Agency for 2022 base year [1]; a useful life of 20 years (Step II) was considered for the wind farms [12, 13]; the wind turbine blade mass determination (Step III) was based on the installed onshore capacity of 6 432.7 MW in the State of Bahia for 2022 base year [1] and an unitary mass of 9.57 tonnes (t) of G-FRP per megawatt (MW) [14]; the MPC coordinates (Step IV) were defined in the CGM according to Eq. 1 and Eq. 2 obtained in [15], which have been used by [16] for locational optimization:

$$x := \frac{\sum(Mi \times Ci \times xi)}{\sum(Mi \times Ci)} \qquad (1)$$

$$y := \frac{\sum(Mi \times Ci \times yi)}{\sum(Mi \times Ci)} \qquad (2)$$

Where:
Mi represents the mass (t) to be transported from the wind farm i to the cement plant;
Ci represents the unitary cost (US$ / (t km)) of transportation;
xi represents a wind farm (km) coordinate in the x axis;
yi represents a wind farm (km) coordinate in the y axis.

For the estimation of Mi, it was considered that wind turbine blades should be reduced in size after decommissioning to simplify transportation [17], in which a wet saw with diamond wire is used to minimize dust and debris. The cut wind turbine blades are then loaded onto the platform of the trucks for transportation to the MPC [18, 19]. Ci was estimated at R$ 0,90 / (t km), considering the round-trip cost from the wind farm to the MPC. The coordinates were defined on the basis of latitude (xi) and longitude (yi) data of wind farms in SIGA [1]. The MPC location was defined based on the projected amount of waste over the next 20 years. The municipality for MPC implementation was identified with the x and y coordinates and use of Google Maps®. The MFA method [20] (Step V) was used to assess the mass balance in logistics of the decommissioned wind turbine blades. For this purpose, the decommissioning of all wind turbine blades of the Brotas de Macaúbas Wind Complex was considered The Brotas de Macaúbas Wind Complex is located in the municipality of Brotas de Macaúbas and consists of three wind farms with a total installed capacity of 95.2 MW: Macaúbas (35 MW), Novo Horizonte (30 MW) and Seabra (30 MW) with an annual production of 313 GWh [1,4]. In total, there are 57 wind turbines: Macaúbas (18), Novo Horizonte (18) and Seabra (21) of the *Alstom ECO86* model with an individual nominal capacity of 1.67 MW [4, 21, 22]. Each wind turbine is equipped with 3 blades on the rotor [22, 23] is 47 m long and 6.5 t in weight for each blade [24]. MFA was conducted in STAN® software version 2.7.101. It was considered that each wind blade is composed of fiberglass fabric (60.4%), epoxy resin (32.3%), balsa wood (2.3%), metal material (1.4%), polyurethane foam (1.7%), protective coating (1.6%) and adhesive (0.3%) on a mass basis [25].

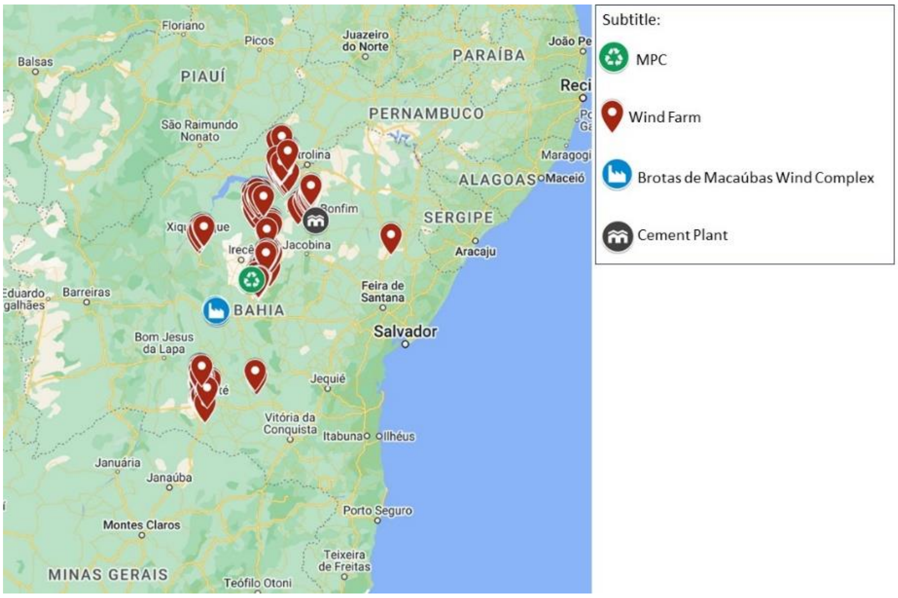
The decommissioned blades are cut 1.5 m^2 sizes at the collection site and then transported by truck in 6.5 t per trip [26] from Brotas de Macaúbas Wind Complex to the MPC. Upon arrival at the MPC, the metal and wood components are segregated, and the remaining material is shredded into pieces lower than 40 mm. The shredded material is mixed with the SRF (Solid Recovery Fuel) in the ratio of 50% G-FRP and

50% SRF [27] and transported by truck to the cement company InterCement Brazil in Campo Formoso for co-processing in the cement kiln [28]. It was considered that the SRF and G-FRP did not receive any further processing other than shredding [27].

3. RESULTS AND DISCUSSION

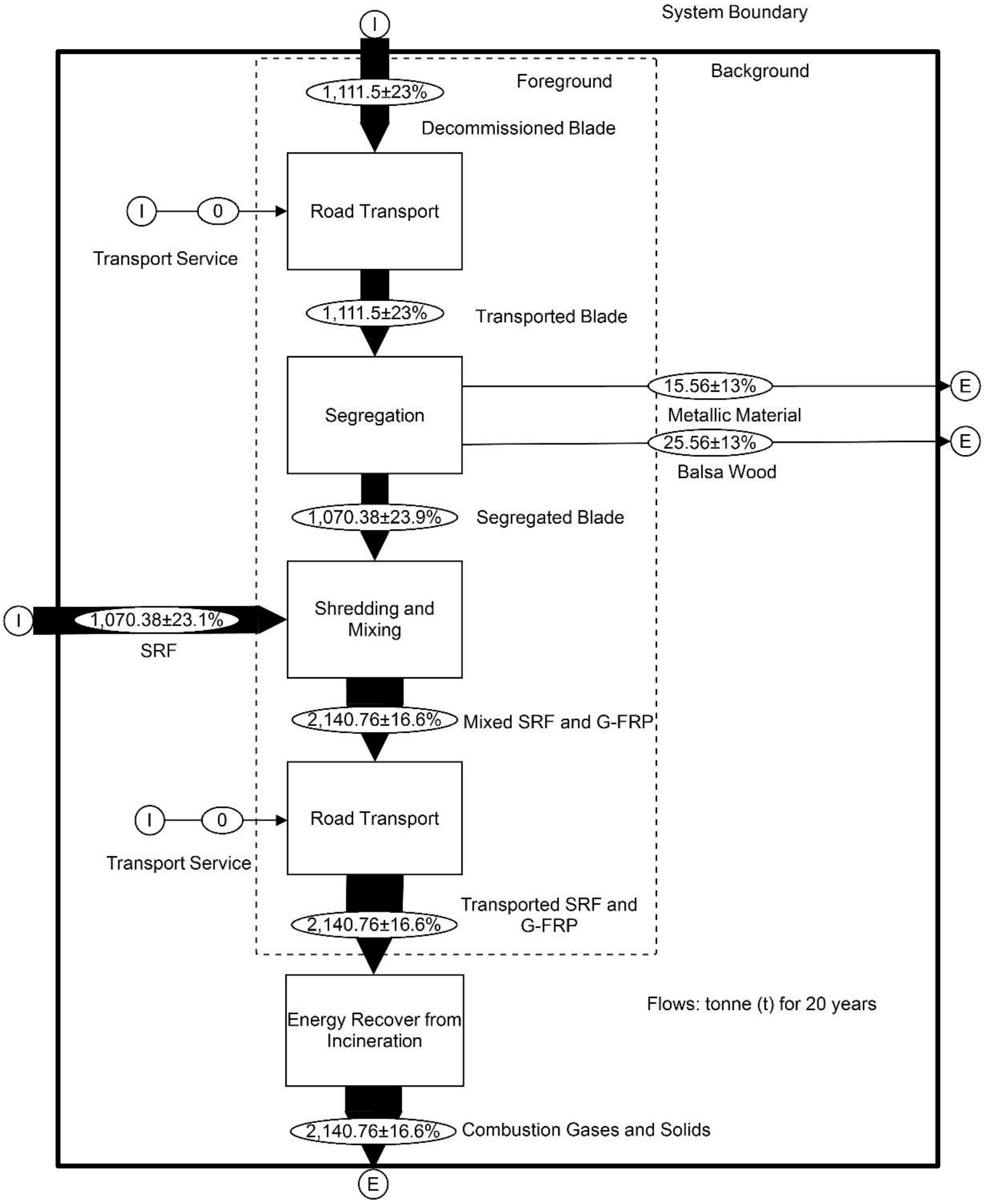
The wind farms in Bahia are located in the interior of the State, unlike the remaining wind farms in the Northeast States, which are mostly located in coastal regions. Figure 1 shows the location of the MPC in the municipality of Canarana that was defined in the CGM: $x = -11{,}6931229$ km e $y = -41{,}63425597$ km. The MPC is located at 136 km from the Brotas de Macaúbas Wind Complex and 286 km away from the cement plant.

Figure 1 - Location of the Wind Farms, Brotas de Macaúbas Wind Complex, Material Processing Center (MPC) and Cement Plant with Coprocessing in Bahia.



Considering that 1 000 kg of G-FRP from decomissioned blades can replace 600 kg of petroleum coke [29], the energy recovery from the wind turbine blades of the Brotas de Macaúbas Wind Complex after decommissioning 1 070 t (Figure 2) can replace 667 t of petroleum coke. Most of the petroleum coke used in Brazilian cement plants is characterized by high sulphur content (6.5% base mass), which comes from the Gulf of Mexico [30]. Therefore, the energy recovery from decommissioned blades can contribute to improving the environmental performance of the wind turbine power and cement sector. In this regard, further studies should be conducted to cover more sustainability indicators to support a robust decision-making in decommissioned blade logistics. The energy recovery from wind turbine blades in cement plants in the State of Bahia is advantageous due to the instability of petroleum coke price used in cement kilns and its high carbon footprint [31]. In addition, the cement industry target is to replace the petroleum coke in the energy matrix by 55% with a more sustainable fuel till 2050 [9].

Figure 2 - Product system of the decomissioned wind turbine blade logistics from Brotas de Macaúbas Wind Complex for energy recovery in a cement kiln. The flows are classified as import (I) or export (E). SRF: solid recovery fuel; G-FRP: glass fiber reinforced polymer.



Source: Authors using STAN® software.

4. CONCLUSION

Energy recovery of decommissioned blades in cement plants is a promising short-term solution in the State of Bahia in Brazil. The current environmental license for material co-processing in a cement plant of the State the highest concentration of wind farms and the cement industry's search for cheaper and less polluting energy sources contribute to the viability of the decommissioned blade destination in the cement kiln. However, it is necessary to evaluate the transportation, segregation, and shredding costs of the decommissioned blade component against the costs of sanitary landfill disposal and petroleum coke import to fuel the cement kilns. Moreover, further studies are required to evaluate the energy and environmental performance of the decommissioned wind turbine blade logistics in Bahia.

5. REFERENCES

[1] ANEEL. SIGA - Sistema de Informações de Geração da ANEEL - Dados Abertos - Agência Nacional de Energia Elétrica. 2022. Disponível em: https://dadosabertos.aneel.gov.br/dataset/siga-sistema-de-informacoes-de-geracao-da-aneel. Acesso em: 1 nov. 2022.

[2] EPE. **Balanço Energético Nacional 2022: Ano Base 2021**. Rio de Janeiro: Empresa de Pesquisa Energética, 2022. Disponível em: https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/balanco-energetico-nacional-2022. Acesso em: 22 abr. 2023.

[3] ABEEÓLICA. **Boletim Anual de Geração Eólica 2021**. São Paulo: Associação Brasileira de Energia Eólica, 2022. Disponível em: https://abeeolica.org.br/energia-eolica/dados-abeeolica/?ano=2022. Acesso em: 1 maio 2022.

[4] STATKRAFT. Complexo Eólico Brotas de Macaúbas. 2023. Disponível em: https://www.statkraft.com.br/onde-operamos/brasil/complexo-eolico-de-brotas-de-macaubas/. Acesso em: 30 jul. 2023.

[5] DORIGATO, A. Recycling of thermosetting composites for wind blade application. **Advanced Industrial and Engineering Polymer Research**, v. 4, n. 2, p. 116–132, abr. 2021. https://doi.org/10.1016/j.aiepr.2021.02.002.

[6] CHEN, J.; WANG, J.; NI, A. Recycling and reuse of composite materials for wind turbine blades: An overview. **Journal of Reinforced Plastics and Composites**, v. 38, n. 12, p. 567–577, jun. 2019. https://doi.org/10.1177/0731684419833470.

[7] MARTINEZ-MARQUEZ, D.; FLORIN, N.; HALL, W.; MAJEWSKI, P.; WANG, H.; STEWART, R. A. State-of-the-art review of product stewardship strategies for large composite wind turbine blades. **Resources, Conservation & Recycling Advances**, v. 15, p. 200109, nov. 2022. https://doi.org/10.1016/j.rcradv.2022.200109.

[8] JENSEN, J. P.; SKELTON, K. Wind turbine blade recycling: Experiences, challenges and possibilities in a circular economy. **Renewable and Sustainable Energy Reviews**, v. 97, p. 165–176, dez. 2018. https://doi.org/10.1016/j.rser.2018.08.041.

[9] ABCP. **Panorama_Coprocessamento_2022_Ano_Base_2021.pdf**. São Paulo: Associação Brasileira de Cimento Portland, 2022. Disponível em: https://coprocessamento.org.br/wp-content/uploads/2022/12/Panorama_Coprocessamento_2022_Ano_Base_2021.pdf. Acesso em: 13 fev. 2023.

[10] ETIPWIND. **How wind is going circular - Blade recycling**. [*S. l.*]: European Techbology & Innovation Platform on Wind Energy, 2019. Disponível em: https://etipwind.eu/publications/. Acesso em: 13 fev. 2023.

[11] BRASIL. Conselho Nacional do Meio Ambiente. Dispõe sobre o licenciamento da atividade de coprocessamento de resíduos em fornos rotativos de produção de clínquer. seç. 1, p. 50, 8 out. 2020. Disponível em: https://www.in.gov.br/en/web/dou/-/resolucao-conama/mma-n-499-de-6-de-outubro-de-2020-281790575.

[12] COOPERMAN, A.; EBERLE, A.; LANTZ, E. Wind turbine blade material in the United States: Quantities, costs, and end-of-life options. **Resources, Conservation and Recycling**, v. 168, p. 105439, maio 2021. https://doi.org/10.1016/j.resconrec.2021.105439.

[13] EPE. Empreendimentos eólicos ao fim da vida útil - Situação Atual e Perspectivas Futuras. Nota Técnica. Brasília: Empresa de Pesquisa Energética, 8 fev. 2021. Disponível em: https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-563/NT-EPE-DEE-012-2021.pdf. Acesso em: 23 abr. 2022.

[14] ARIAS, F.; BANK, L. Assessment of Present/Future Decommissioned Wind Blade Fiber-Reinforced Composite Material in the United States. City College of New York, p. 69, 2016.

[15] MARTINS, P. G.; LAUGENI, F. P. **Administração da produção**. 3ª edição. [*S. l.*]: Saraiva Uni, 2015.

[16] BITTENCOURT, B. N.; SERVARE JUNIOR, M. W. J. CENTRO DE GRAVIDADE PARA LOCALIZAR CENTRO DE COLETA PARA A ECONOMIA CIRCULAR DO ÓLEO DE COZINHA EM VITÓRIA, ES: GRAVITY CENTER TO LOCATE A COLLECTION CENTER FOR THE CIRCULAR ECONOMY OF COOKING OIL IN VITÓRIA, ES. **Brazilian Journal of Production Engineering - BJPE**, , p. 194–206, 14 dez. 2021. https://doi.org/10.47456/bjpe.v7i5.37047.

[17] SULTAN, A. A. M.; MATIVENGA, P. T.; LOU, E. Managing Supply Chain Complexity: Foresight for Wind Turbine Composite Waste. **Procedia CIRP**, v. 69, p. 938–943, 2018. https://doi.org/10.1016/j.procir.2017.11.027.

[18] MARTIN, C. Wind Turbine Blades Can't Be Recycled, So They're Piling Up in Landfills. **Bloomberg.com**, 5 fev. 2020. Disponível em: https://www.bloomberg.com/news/features/2020-02-05/wind-turbine-blades-can-t-be-recycled-so-they-re-piling-up-in-landfills. Acesso em: 16 abr. 2023.

[19] RIVERCAP. Fiberglass Recycling | RiverCap. 2023. Disponível em: https://www.rivercapllc.com/fiberglass-recycling. Acesso em: 13 fev. 2023.

[20] BRUNNER, P. H.; RECHBERGER, H. **Practical Handbook of Material Flow Analysis**. 0 ed. [*S. l.*]: CRC Press, 2003. DOI 10.1201/9780203507209. Disponível em: https://www.taylorfrancis.com/books/9780203507209. Acesso em: 23 jun. 2022.

[21] ALSTOM. Aerogeradores da Alstom ofereceram o mais alto rendimento no mercado brasileiro nos últimos doze meses. 2014. **Alstom**. Disponível em: https://www.alstom.com/pt/press-releases-news/2014/8/aerogeradores-da-alstom-ofereceram-o-mais-alto-rendimento-no-mercado-brasileiro-nos-ultimos-doze-meses. Acesso em: 30 jul. 2023.

[22] DIAS, B. A. Energia eólica e o estudo de caso do Parque Eólico de Brotas de Macaúbas. mar. 2015. Disponível em: http://dspace.sti.ufcg.edu.br:8080/jspui/handle/riufcg/18485. Acesso em: 30 jul. 2023.

[23] BAUER, L.; MATYSIK, S. Alstom ECO 86 - 1,67 MW - Wind turbine. 2023. Disponível em: https://en.wind-turbine-models.com/turbines/794-alstom-eco-86. Acesso em: 30 jul. 2023.

[24] GOVERNO DO ESTADO DA BAHIA. **Brotas de Macaúbas recebe hélices para aerogeradores de parque eólico**. 16 mar. 2011. **Portal Gov Bahia**. Disponível em: https://www.bahia.ba.gov.br/2011/03/noticias/industria/brotas-de-macaubas-recebe-helices-para-aerogeradores-de-parque-eolico/. Acesso em: 30 jul. 2023.

[25] LIU, P.; BARLOW, C. Y. The environmental impact of wind turbine blades. **IOP Conference Series: Materials Science and Engineering**, v. 139, p. 012032, jul. 2016. https://doi.org/10.1088/1757-899X/139/1/012032.

[26] NAGLE, A. J.; DELANEY, E. L.; BANK, L. C.; LEAHY, P. G. A Comparative Life Cycle Assessment between landfilling and Co-Processing of waste from decommissioned Irish wind turbine blades. **Journal of Cleaner Production**, v. 277, p. 123321, dez. 2020. https://doi.org/10.1016/j.jclepro.2020.123321.

[27] INTERCEMENT BRASIL. Institucional. 2023. **Intercement Brasil**. Disponível em: https://brasil.intercement.com/institucional/. Acesso em: 2 abr. 2023.

[28] EPRI. **Wind Turbine Blade Recycling: Preliminary Assessment**. Techinical Report, n. Eletric Power Research Institute. California: EPRI, 2020. Disponível em: https://www.epri.com/research/products/000000003002017711. Acesso em: 8 maio 2023.

[29] LIU, P.; MENG, F.; BARLOW, C. Y. Wind turbine blade end-of-life options: An eco-audit comparison. **Journal of Cleaner Production**, v. 212, p. 1268–1281, mar. 2019. https://doi.org/10.1016/j.jclepro.2018.12.043.

[30] ROLAND JUNIOR, G. R. O.; ZATTAR, I. C. GESTÃO DA CADEIA DE SUPRIMENTOS DO COQUE DE PETROLEO NA INDÚSTRIA CIMENTEIRA. 2 dez. 2022. **Anais do ConBRepro 2022** [...]. Universidade Tecnológica Federal do Paraná: [*s. n.*], 2 dez. 2022. p. 12. Disponível em: https://aprepro.org.br/conbrepro/anais/. Acesso em: 22 maio 2023.

[31] TORRES, V. A.; LANGE, L. C. Rotas tecnológicas, desafios e potencial para valoração energética de resíduo sólido urbano por coprocessamento no Brasil. **Engenharia Sanitária e Ambiental**, v. 27, n. 1, p. 25–30, fev. 2022. https://doi.org/10.1590/s1413-415220210221.