05-001

OPTIMAL LOCATION FOR RECYCLING OF WIND TURBINE BLADES: A CHALLENGE FOR THE CIRCULAR ECONOMY

Gil García, Isabel C. [(1)]; Fernández Guillamón, Ana [(2)]; Ramos Escudero, Adela [(3)]; García Cascales, M.Socorro [(3)]; Molina García, Ángel [(3)]

[(1)] Universidad a distancia de Madrid (UDIMA), [(2)] Universidad de Castilla - La Mancha (UCLM), [(3)] Universidad Politécnica de Cartagena (UPCT)

The accelerated path towards the decarbonization of the economy has raised the demand for wind capacity at an exponential rate, at the end of 2021 the global installed capacity reached 840 GW. The useful life of the turbines ranges between 20 and 25 years, which implies that the volume of recyclable material increases proportionally. Currently, 85% of wind turbines are recycled, but the goal is to achieve a recyclability rate of 100%. The blades represent a challenge for the sector, their complex composition of fiberglass, carbon or different resins, make the recycling process difficult. There are different technologies such as mechanical, thermal and chemical recycling that are constantly improving. In fact, the European Union has given priority to the financing of recycling projects, specifically Spain, from the Ministry of Ecological Transition it proposes a line of 150 million euros for different aid programs, including the blade recycling program. In this area, the main objective of this work is to propose an optimal location methodology for blade recycling companies, incorporating economic, technical, political and environmental factors that favor the principles of the circular economy

Keywords: wind energy; recycling, blades; circular economy; optimal location

UBICACIÓN ÓPTIMA PARA RECICLAJE DE PALAS DE AEROGENERADORES: DESAFÍO PARA LA ECONOMÍA CIRCULAR

El camino acelerado hacia la descarbonización de la economía ha elevado la demanda de capacidad eólica a un ritmo exponencial, a finales del año 2021 la capacidad global instalada alcanzó los 840 GW. La vida útil de las turbinas oscila entre 20 y 25 años, lo que implica que el volumen de material reciclable aumente proporcionalmente. En la actualidad, el 85% de las turbinas eólicas se reciclan, pero el objetivo es alcanzar una tasa de reciclabilidad del 100 %. Las palas representan un desafío para el sector, su compleja composición de fibra de vidrio, carbono o diferentes resinas, dificultan el proceso de reciclado. Existen diferentes tecnologías como el reciclaje mecánico, térmico y químico que se encuentran en constante mejora. De hecho, la unión europea ha dado prioridad para la financiación de proyectos de reciclaje, específicamente España, desde el ministerio de transición ecológica propone una línea de 150 millones de euros para diferentes programas de ayuda, entre ellos el programa de reciclaje de palas. En este ámbito, el objetivo principal de este trabajo es proponer una metodología de localización óptima de empresas de reciclado de palas, incorporando factores: económicos, técnicos, políticos y ambientales que favorezcan los principios de la economía circular

Palabras clave: energía eólica; reciclaje, palas; economía circular; localización óptima

Agradecimientos: This work was partially supported by the Ministry of Science and Innovation, Spain (Ref. PID2021--126082OB--C22)

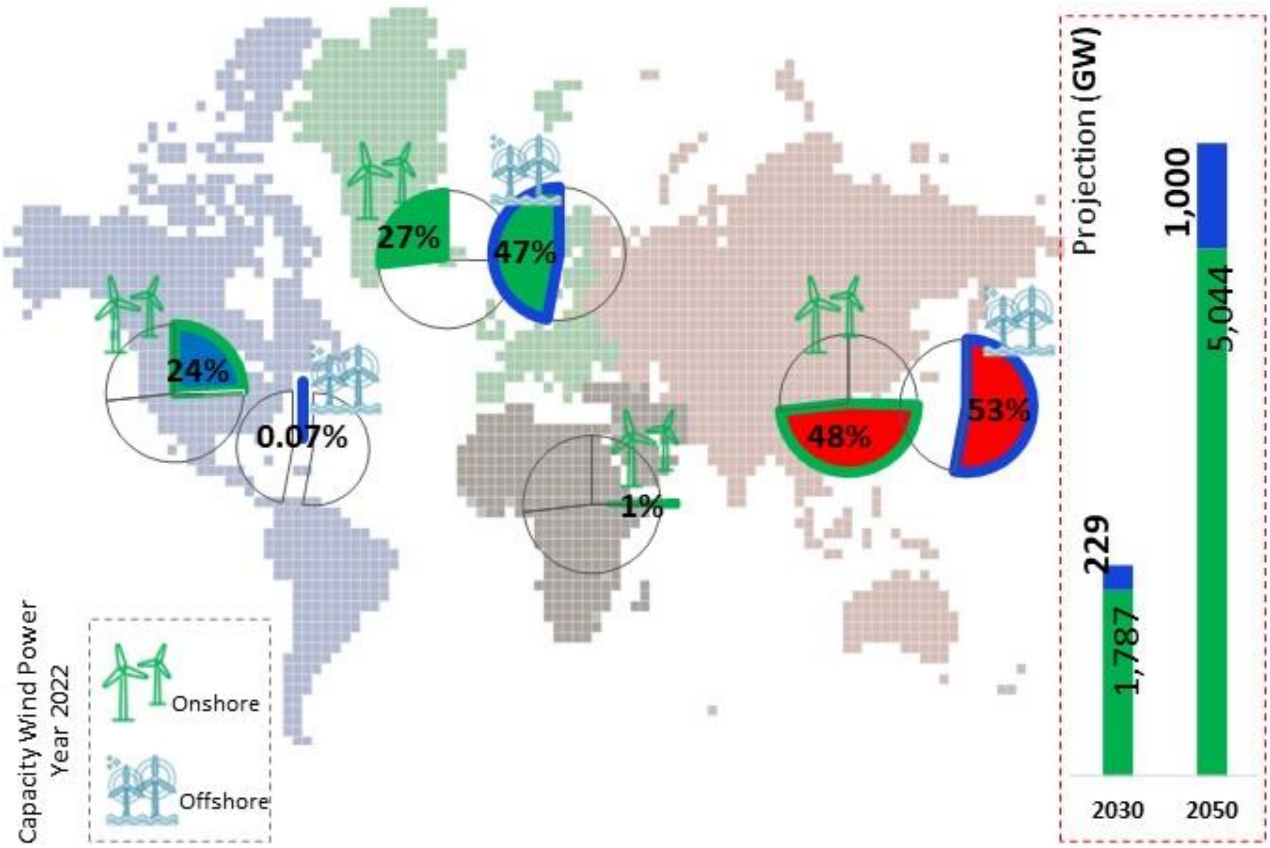
1. Introduction

Extreme weather events continue to prevail on the planet [1], [2], the need to meet decarbonization targets is a global priority task [3]. The implementation of renewable energy plants, is considered the backbone for the change from a system based on fossil fuels to clean energy systems [4]. [5]

Countries and organizations are aligned with the transition, in fact, the renewable capacity does not stop growing, in the last decade 1,737.62 GW have been added, totaling 3,068.3 GW at the end of 2021 [6], among them wind power stands out, which is growing exponentially in volume and is increasingly distributed geographically.

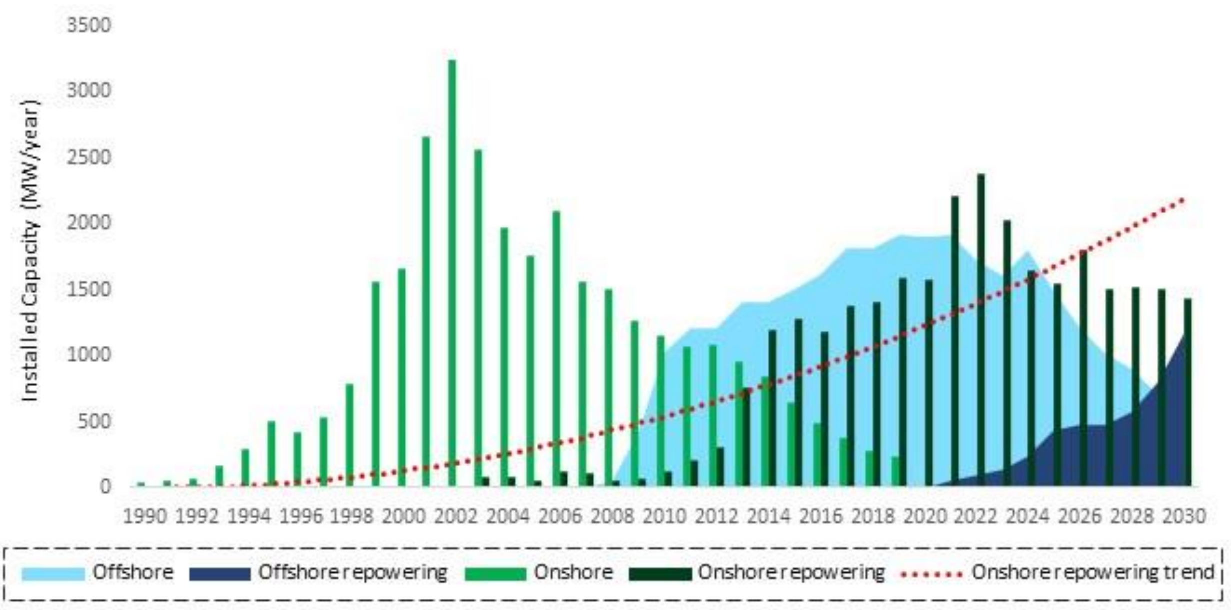
In 2022, 68.8 GW of new onshore wind capacity was registered globally, bringing the cumulative onshore wind capacity to 842 GW. The Asia-Pacific region leads the ranking with more than 402 GW of total installed capacity, representing 48% of the total. The top five onshore wind markets are China (32.6 GW), the US (8.6 GW), Brazil (4.1 GW), Sweden (2.4 GW), and Finland (2.4 GW). A record in the history of global offshore wind power was recorded, 8.77 GW of offshore wind power was connected to the grid globally, bringing the total offshore wind capacity to 64.3 GW. The Asia-Pacific region leads the ranking with almost 34 GW, 53% of the total; very closely Europe with 30 GW-47%. The upward trend prevails in the wind sector for the projections of the next three decades. In the years 2030 and 2050, electricity generation of more than 18,000 TWh is expected. [7], see **Figure 1**.

Figure 1. Installed capacity at the end of 2022. Projection for the years 2030 and 2050. Own elaboration from [7]



However, the useful life of these plants is approximately between 20 and 25 years [8], the wind farms have the option of partially or totally repowering or dismantling their turbines, therefore, the repowering or decommissioning scenario is a symmetrical pattern to the new installation's scenario, most of the new installed capacity will be replaced by new technology, usually with higher power. For example, the case of Germany, since 2003 is practically a symmetry of the scenario of new plants in the period 1990-2020 [3], see **Figure 2**.

Figure 2. Annual installed capacity versus repowering market. Germany. Source: [3]



Both the repowering, the dismantling and the manufacturing of new turbines imply a complex waste treatment process. Most of the components of a wind turbine, such as the foundation, the tower, the gearbox components and the generator are already recyclable [9], however, the blades of wind turbines, with a complex composition of materials, represent a challenge for the sector [10].

The wind sector, organizations and different countries are committed to executing sustainable processes, maximizing environmental benefits and promoting the circular economy. Europe's wind industry actively commits to re-use, recycle, or recover 100% of decommissioned blades [11] In Spain, the Ministry for the Ecological Transition and the Demographic Challenge (MITECO) has released three aid programs to the public, including the recycling of wind turbine blades, initially endowed with 150 million euros, it is expected to reach an annual recycling capacity of about 19,000 tons of blades [12]. Vestas, a leading company in the sector, promotes the CETEC (Circular Economy for Thermosets Epoxy Composites) project, where a new technology is developed to increase the circularity of thermosetting epoxy resins [13].

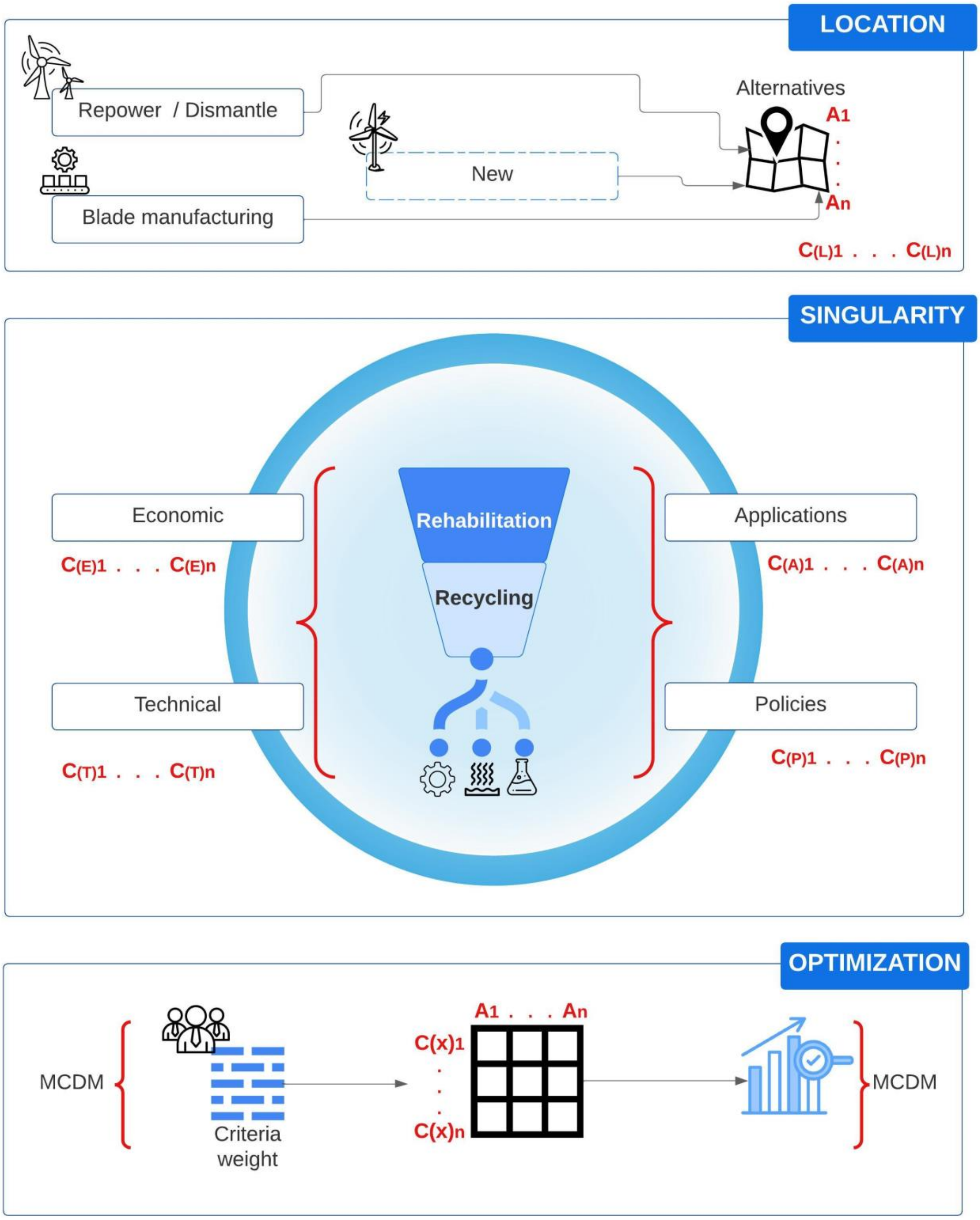
In this ambit, the main objective of this communication is to propose a methodology for the optimal location of blade recycling companies, incorporating economic, technical and environmental factors that favor the principles of the circular economy, as well as describing the types of blade recycling that currently exist.

The rest of the work is organized as follows: Section 2 describes the methodological proposal, Section 3 presents the results of a case study; finally, the conclusions are given in Section 4.

2. Methodology

The methodological proposal is grouped in three phases: “Localization”, “Singularity” and “Optimization”, see **Figure 3**.

Figure 3. Overview of the proposed methodology. Own elaboration



2.1. Phases

2.1.1 Location

The first phase "Localization" aims to select the potential alternatives of blade recycling companies, based on the continuous existence of raw material (blades). The alternatives will be designed preferably in industrial parks close to:

- Actual wind power plants close to repowering or dismantling.
- Blade factories with the objective of taking advantage of surplus
- Future wind power plants, to be repowered in a period of 20-25 years.

The above points constitute the location criteria ($C_{(L)1}$...$C_{(L)3}$), the objective function is to minimize distances, see **Table 1**. The different alternatives will be coded from A_1 to A_n.

In this process it is very useful to use GIS (Geographic information system) viewers with layers that include the information of these criteria, so that the calculation of the distances of each alternative is automatic. The study can be carried out for different areas, be it a province, a country, a continent, etc.

Table 1. Location criteria

Criteria		Unit	Function Objective
Average distance to wind power plants between 15 and 25 years	$C_{(L)1}$		
Average distance to blade factories	$C_{(L)2}$	km	Minimize
Average distance to future wind farms	$C_{(L)3}$		

2.1.2. Singularity

The “Singularity” phase consists of assigning attributes to the potential alternatives defined in the previous step, these can be from different fields: technical, economic, political and those related to the possible destinations of the products obtained, focused on the principles of the circular economy [14].

It is important to note that the types of blades recycling companies, for the case of Europe, must be aligned with the waste hierarchy established by the EU in Directive 2008/98/EC on Waste Management [15], where before recycling, reuse or rehabilitation (see section 2.2) must be attempted. If this is not possible, a complex recycling process can be applied, there are three types: mechanical, thermal, and chemical (see section 2.3).

Due to the complex composition of the blades, mainly thermosetting resins, recycling processes are mostly in the research phase. The Technology Readiness Level (TRL) has been studied by different authors compared to costs [16] and waste management [17], see **Figure 4**. The technical criteria are defined by TRL ($C_{(T)1}$) and the processing capacity ($C_{(T)2}$). Economic criteria Capital Expenditure(CAPEX)($C_{(E)1}$) and Operational expenditures (OPEX)($C_{(E)2}$) see **Table 2**.

The possible applications of the generated product as well as its commercialization endow the wind blades with circularity. If the blades are directly reused, the circular economy is favored; if they are recycled, it is important to highlight the creation of new products that incorporate the full value of the composite material. Achieving a continuous flow of the generated volume, transformed into a new by-product, requires a commercial figure in charge of linking and training in the use of this new raw material. Applications criteria are defined under these premises: Product generated ($C_{(A)1}$) and Commercialization ($C_{(A)2}$). As we have been able to verify that these companies are currently unviable, the measures and aid plans adopted by governments and organizations committed to the circular economy and the environment are essential to ensure technological maturity and economic viability, which guarantee their existence. The political criterion is focused on this point, the existence of investment aid ($C_{(P)1}$), see **Table 3**.

Figure 4. Recycling processes. TLR/Cost. Own elaboration from [16]

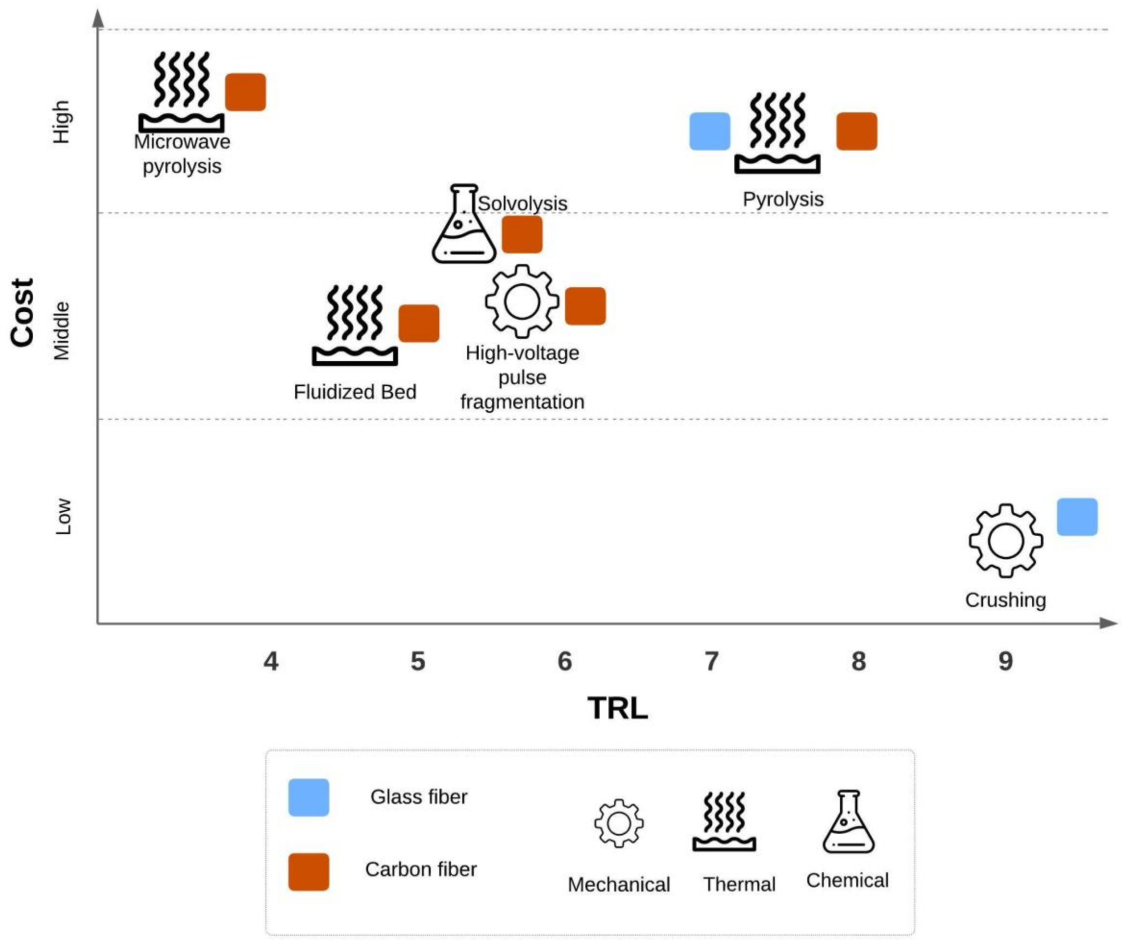


Table 2. Technical and Economic Criteria

Criteria		Unit	Function Objective
Technology Readiness Level	$C_{(T)1}$	Scale	Maximize
Processing Capacity	$C_{(T)2}$	tn/year	Maximize
CAPEX	$C_{(E)1}$	monetary	Minimize
OPEX	$C_{(E)2}$	monetary	Minimize

Table 3. Applications and Political Criteria

Criteria		Unit	Function Objective
Product generated	$C_{(A)1}$	Scale	Maximize
Commercialization	$C_{(A)2}$	Scale	Maximize
Existence of investment aid	$C_{(P)1}$	Scale	Maximize

2.1.3. Optimization

The optimization phase aims to order the alternatives in a descending order according to their favorability to the circular economy using Multicriteria Evaluation Methods.

The attributes assigned to each pair [Alternative-Criteria] according to their objective function make up the decision matrix.

The criteria, the most important indicators, detailed in the previous phases are examined by a group of experts to determine the weight. There are several methods, for example:

- Analytic Hierarchical Process (AHP) method proposed by Saaty [18]. The model is characterized by its hierarchy, the top level represents the goal to be achieved, the intermediate level incorporates all the levels of criteria and sub-criteria that link the model and at the base are the alternatives that will be evaluated, although the model can be used to evaluate alternatives, in this methodology it is used to calculate the weights according to the following steps [19]:
    1. Design the hierarchical model of the problem.
    2. Assigning and assessing priorities.
- Entropy: employs the initial decision matrix to compute criteria weights, therefore eliminates the subjectivity of expert judgements, the steps are [20]:
    1. Normalized the decision matrix.
    2. Compute the criteria entropy values.
    3. Estimate criterion objective weight.

There are other methods that can be used, but the nature of the criteria is better suited to these methods [21].

The ranking of alternatives is obtained using different methods, depending on many factors such as the nature of the criteria, for example:

- Topsis (Technique for Order of Preference by Similarity to Ideal Solution): Works with solutions close to the ideal and away from the anti-ideal solution [19].
- Vikor: Determines the solution as the alternative that is the shortest distance away from the ideal solution [22].
- Electre-Tri (ELimination Et Choix Traduisant la REalité): Assigns previously defined categories to a group of alternatives [23].
- SIMUS (Sequential Interactive Modeling for Urban Systems): Procedure based on linear programming [24].

Each method operates according to a specific procedure, the TOPSIS method performs the following sequence: 1-Normalization of the decision matrix, 2-Construction of the weighted normalized matrix,3-Determination of the ideal positive and negative solution, 4-Calculation of the positive and negative ideal solution, 5Calculation of the relative proximity of each alternative to the positive ideal solution positive ideal solution and finally 6-Ordering of the alternatives according to their relative proximity.

2.2. Rehabilitation and Reuse

The rehabilitation of used blades is a practical solution in the dismantling of wind turbines, so that it can be reused in another plant and extend its useful life, in fact there are companies that certify the life extension through a technical and feasibility study, for example: DNV-GL [25]includes the blades in the life extension standards of wind turbines [26], SGS certifies this extension through its own certification SGS ECPE-2056 [27].

Once the certification process has been completed, there are companies that specialize in the sale/purchase of parts, accessories, etc., such as Wind-Turbine [28].

Another option is the reuse in other sectors other than wind energy, taking advantage of its mechanical qualities, in the urban planning, architectural sector, etc. The company SuperUse [29] has developed several projects for the reuse of blades in playgrounds, see **Figure *5***.

Figure 5. Blade Made playgrounds. *Own elaboration from* [29]

Another leading example in the reuse of blades is the Re-Wind group [30], which published its "Design Atlas" where they propose multiple possible alternative uses for the blades, including: wave attenuators in coastal areas, telecommunication towers, bleacher seats, acoustic barriers on roads, material for 3D printing, telecommunication towers, bridges, foundations, roof sections in buildings, ventilation systems, water pipelines, skate park etc. [31]

2.3. Types of recycling of blades

In previous sections we have referred to the different types of recycling, so that the blades become a new product.

2.3.1. Mechanical Recycling

The blades are shredded into millimetric portions, subsequently processed and new products are obtained [32]. In this type of recycling, the blades are shredded into large fragments at the wind farm itself, thus reducing the cost of transportation. The resulting product can be used as raw material to produce new plastic products, cement or as fillers and reinforcements [33]. In general, it is an efficient process because of its low cost and the little energy used, but the value of the glass fibers disappears completely. High voltage pulse fragmentation is an electromechanical process that separates the matrices from the fibers in composite materials by using electricity.

The most developed application is the production of cement, part of the calcium carbonate ($CaCO_3$) in cement is replaced by glass fibers, significantly reducing the CO_2 generation associated with cement production. Some examples:

- Holcim Lägerdorf plant in Germany [34]
- In the United States, in 2020, General Electric Renewable Energy [35] and Veolia [36]signed an agreement to use mechanically recycled material from blades for cement production. This solution is doubly favorable for the environment, on the one hand it recycles the blades and on the other hand it is expected to reduce 27% of emissions in cement production [5].

2.3.2. Thermal Recycling

The objective of this recycling is to obtain the fibers, by applying thermal processes to the waste blades, so that organic combustion occurs. There are several alternatives:

- Pyrolysis: Thermal decomposition of materials at high temperatures in the absence of oxygen. This is a recycling process that is already used for other applications, the polymeric matrix is degraded to a mixture of hydrocarbons, obtaining glass fibers as a product of the process. [37]. For the moment, the investment cost is very high, however it is the most developed technology within the thermal processes.
- Microwave pyrolysis: It is very similar to pyrolysis, but the material is heated by microwave radiation, which allows uniform heating throughout the part and greater control. Less degradation of the glass fibers is obtained than with pyrolysis [38].
- Fluidized beds: The objective is the combustion of the fibers in the fluidized bed reactor to temperatures up to 550 ºC, previously the blades are crushed in small sizes. It allows better retention of the mechanical properties and value of the material compared to previous methods [39]. It is the most economical of the thermal processes, but it is a much less mature technology than pyrolysis.

2.3.3. Chemical Recycling

The most common method is solvolysis, a method that uses a solvent composed of catalysts (water in the case of blades) to depolymerize the cross-linked chemical bond present in thermoset polymer products. The composite material melts under the action of the chemical solvent, breaking the resin bonds [37]. Both carbon and glass fibers are recovered [40].

3. Results

The proposed methodology has been evaluated in Spain. Initially, the potential wind resource areas, current wind power plants and blade manufacturing plants were processed in a GIS viewer. Two potential regions are located, the community of Navarra and the community of Castilla la Mancha with 18 and 25 alternatives.

The alternative located in the first position of the ranking, has the following characteristics:

- It is located in the community of Navarra, with several wind power plants nearby, blade manufacturing plants and a wide deployment of new plants.
- It will have two lines, one for the reuse and commercialization of used blades and the other for mechanical recycling.
- TRL and processing capacity of both lines is considered high.
- Investment and maintenance costs are considered low, taking into account the national and regional subsidies for this type of company.
- The product generated obtains an average score in the case of the recycling line, since the value of the composite material is not lost.
- The commercialization of the products of both lines and therefore the favoring of the circular economy is high, the region has a consolidated cement industry.

Optimization was performed with the combination of Entropy + Vikor multicriteria evaluation methods.

4. Conclusions

The installed capacity of onshore and offshore wind power plants is increasing exponentially, which implies the inevitable dismantling or repowering 20 years later and the subsequent recycling of all its parts.

At present, there are different methods for recycling blades, most of which are in the experimental phase. The mechanical recycling method is the most technologically mature and fairly consolidated on a commercial scale; however, stable commercial synergies are required to consolidate the raw material obtained from blade recycling in cement production. It should be noted that this is not the best option, since the value of the composite material is lost, which is why investments in research are required in order to achieve the commercial development of these recycling processes, making these plants viable.

This paper proposes a methodology to optimally locate these new recycling companies, taking into account a series of factors: economic, technical, political, location and possible applications, all of which together favor the circular economy, a complex problem that the authors solve using multi-criteria evaluation methods.

The methodology is evaluated in Spain, two communities are ranked as potential with 43 alternatives. The best alternative has a double solution to the problem of dismantled blades, a reuse line and a mechanical recycling line, with possible synergies with the cement industry, achieving a double objective: the reduction of emissions from the cement sector and the promotion of the circular economy.

The biggest challenge for the wind energy sector is, on the one hand, the recycling of blades due to their complex composition, and on the other hand, the need for changes in new blade designs in order to minimize the volume of waste.

5. References

[1] G. Zittis *et al.*, “Climate Change and Weather Extremes in the Eastern Mediterranean and Middle East,” *Reviews of Geophysics*, vol. 60, no. 3, Sep. 2022, doi: 10.1029/2021RG000762.

[2] L. Kemp *et al.*, “Climate Endgame: Exploring catastrophic climate change scenarios,” *Proceedings of the National Academy of Sciences*, vol. 119, no. 34, Aug. 2022, doi: 10.1073/pnas.2108146119.

[3] I. C. Gil-Garcia, A. Fernandez-Guillamon, A. Molina-Garcia, and M. S. Garcia-Cascales, “A Novel Multi-Criteria Decision-Making Method for Wind Power Plant Repowering,” in *2022 IEEE International Conference on Environment and Electrical Engineering and 2022 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, IEEE, Jun. 2022, pp. 1–5. doi: 10.1109/EEEIC/ICPSEurope54979.2022.9854765.

[4] K. Guerra, R. Gutiérrez-Alvarez, O. J. Guerra, and P. Haro, “Opportunities for low-carbon generation and storage technologies to decarbonise the future power system,” *Appl Energy*, vol. 336, p. 120828, Apr. 2023, doi: 10.1016/j.apenergy.2023.120828.

[5] “Cementeras queman palas mientras eólicas tienen problemas para su reciclaje - noticias de negocios.” https://www.axisnegocios.com/articulo.phtml?id=107557 (accessed Mar. 31, 2023).

[6] “Statistics Time Series.” https://www.irena.org/Data/View-data-by-topic/Capacity-and-Generation/Statistics-Time-Series (accessed Mar. 14, 2023).

[7] “Global Wind Report 2022 - Global Wind Energy Council.” https://gwec.net/global-wind-report-2022/ (accessed Mar. 16, 2023).

[8] J. P. Jensen, “Evaluating the environmental impacts of recycling wind turbines,” *Wind Energy*, vol. 22, no. 2, pp. 316–326, Feb. 2019, doi: 10.1002/we.2287.

[9] J. P. Jensen and K. Skelton, “Wind turbine blade recycling: Experiences, challenges and possibilities in a circular economy,” *Renewable and Sustainable Energy Reviews*, vol. 97, pp. 165–176, Dec. 2018, doi: 10.1016/j.rser.2018.08.041.

[10] K. Korniejenko, B. Kozub, A. Bąk, P. Balamurugan, M. Uthayakumar, and G. Furtos, “Tackling the Circular Economy Challenges—Composites Recycling: Used Tyres, Wind Turbine Blades, and Solar Panels,” *Journal of Composites Science*, vol. 5, no. 9, p. 243, Sep. 2021, doi: 10.3390/jcs5090243.

[11] “Wind industry calls for Europe-wide ban on landfilling turbine blades | WindEurope.” https://windeurope.org/newsroom/press-releases/wind-industry-calls-for-europe-wide-ban-on-landfilling-turbine-blades/ (accessed Mar. 18, 2023).

[12] “El MITECO abre a audiencia pública una línea con 150 millones para repotenciación eólica, minihidráulica y reciclaje de palas.” https://www.miteco.gob.es/es/prensa/ultimas-noticias/el-miteco-abre-a-audiencia-p%C3%BAblica-una-l%C3%ADnea-con-150-millones-para-repotenciaci%C3%B3n-e%C3%B3lica-minihidr%C3%A1ulica-y-reciclaje-de-palas-/tcm:30-541248 (accessed Mar. 18, 2023).

[13] “Zero-Waste.” https://www.vestas.com/en/sustainability/environment/zero-waste (accessed Mar. 18, 2023).

[14] E. Macarthur, “Founding Partners of the TOWARDS THE CIRCULAR ECONOMY Economic and business rationale for an accelerated transition”.

[15] "EUR-Lex - 32008L0098 - EN - EUR-Lex." https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex%3A32008L0098 (accessed Mar. 28, 2023).

[16] "Accelerating Wind Turbine Blade Circularity," 2018.

[17] E. B. Paulsen and P. Enevoldsen, "A Multidisciplinary Review of Recycling Methods for End-of-Life Wind Turbine Blades," *Energies (Basel)*, vol. 14, no. 14, p. 4247, Jul. 2021, doi: 10.3390/en14144247.

[18] T. L. Saaty, "What is the Analytic Hierarchy Process?," in *Mathematical Models for Decision Support*, Berlin, Heidelberg: Springer Berlin Heidelberg, 1988, pp. 109–121. doi: 10.1007/978-3-642-83555-1_5.

[19] I. C. Gil-García, A. Ramos-Escudero, M. S. García-Cascales, H. Dagher, and A. Molina-García, "Fuzzy GIS-based MCDM solution for the optimal offshore wind site selection: The Gulf of Maine case," *Renew Energy*, vol. 183, pp. 130–147, Jan. 2022, doi: 10.1016/j.renene.2021.10.058.

[20] F. Odoi-Yorke, T. F. Adu, B. C. Ampimah, and L. Atepor, "Techno-economic assessment of a utility-scale wind power plant in Ghana," *Energy Conversion and Management: X*, vol. 18, p. 100375, Apr. 2023, doi: 10.1016/j.ecmx.2023.100375.

[21] M. S. García Cascales, "Métodos para la comparación de alternativas mediante un Sistema de Ayuda a la Decisión SAD y "Soft Computing"," May 2009, doi: 10.31428/10317/1022.

[22] J. R. San Cristóbal, "Multi-criteria decision-making in the selection of a renewable energy project in spain: The Vikor method," *Renew Energy*, vol. 36, no. 2, pp. 498–502, Feb. 2011, doi: 10.1016/j.renene.2010.07.031.

[23] G. R. D'Avignon and M. Sauvageau, "L'aide multicritère à la décision : un cas d'intégration de critères techniques, économiques et environnementaux à Hydro-Québec," *RAIRO - Operations Research - Recherche Opérationnelle*, vol. 30, no. 3, pp. 317–332, 1996, Accessed: Mar. 30, 2023. [Online]. Available: http://www.

[24] "Multicriteria Decision-Making by SIMUS." https://sites.google.com/site/decisionmakingmulticriteria/home (accessed Mar. 30, 2023).

[25] "DNV.us - When trust matters - DNV." https://www.dnv.us/?_ga=2.85916505.1392909578.1680086729-1229552884.1680086729 (accessed Mar. 29, 2023).

[26] "DNV-ST-0262 Lifetime extension of wind turbines - DNV." https://www.dnv.com/energy/standards-guidelines/dnv-st-0262-lifetime-extension-of-wind-turbines.html (accessed Mar. 29, 2023).

[27] "SGS Spain | We are the world's leading testing, inspection and certification company." https://www.sgs.com/en-es (accessed Mar. 29, 2023).

[28] "Internationaler Marktplatz der windindustrie - wind-turbine.com." https://wind-turbine.com/ (accessed Mar. 29, 2023).

[29] "Blade Made Playgrounds - Superuse Studios." https://www.superuse-studios.com/projectplus/blade-made/ (accessed Mar. 29, 2023).

[30] "RE.WIND by Fibervent & SRG - Material eólico descatalogado." http://www.re-wind.es/index.html (accessed Mar. 29, 2023).

[31] "Re-Wind releases its Design Atlas for Repurposing Wind Blades under Creative Commons License CC BY-NC-SA 4.0 — The Re-Wind Network." https://www.re-

wind.info/update/2020/8/5/re-wind-releases-its-design-atlas-for-repurposing-wind-blades-under-creative-commons-license-cc-by-nc-sa-40 (accessed Mar. 29, 2023).

[32] R. Cherrington *et al.*, "Producer responsibility: Defining the incentive for recycling composite wind turbine blades in Europe," *Energy Policy*, vol. 47, pp. 13–21, Aug. 2012, doi: 10.1016/j.enpol.2012.03.076.

[33] J. Chen, J. Wang, and A. Ni, "Recycling and reuse of composite materials for wind turbine blades: An overview," *Journal of Reinforced Plastics and Composites*, vol. 38, no. 12, pp. 567–577, Jun. 2019, doi: 10.1177/0731684419833470.

[34] "Holcim Deutschland." https://www.holcim.de/de (accessed Mar. 31, 2023).

[35] "Wind Energy Power Systems & Solutions | GE Renewable Energy." https://www.ge.com/renewableenergy/wind-energy (accessed Mar. 31, 2023).

[36] "Veolia is acting for ecological transformation | Veolia." https://www.veolia.com/en (accessed Mar. 31, 2023).

[37] Y. Yang, R. Boom, B. Irion, D.-J. van Heerden, P. Kuiper, and H. de Wit, "Recycling of composite materials," *Chemical Engineering and Processing: Process Intensification*, vol. 51, pp. 53–68, Jan. 2012, doi: 10.1016/j.cep.2011.09.007.

[38] D. Åkesson, Z. Foltynowicz, J. Christéen, and M. Skrifvars, "Microwave pyrolysis as a method of recycling glass fibre from used blades of wind turbines," *Journal of Reinforced Plastics and Composites*, vol. 31, no. 17, pp. 1136–1142, Sep. 2012, doi: 10.1177/0731684412453512.

[39] K. Kalkanis, C. S. Psomopoulos, S. Kaminaris, G. Ioannidis, and P. Pachos, "Wind turbine blade composite materials - End of life treatment methods," *Energy Procedia*, vol. 157, pp. 1136–1143, Jan. 2019, doi: 10.1016/j.egypro.2018.11.281.

[40] G. Oliveux, L. O. Dandy, and G. A. Leeke, "Current status of recycling of fibre reinforced polymers: Review of technologies, reuse and resulting properties," *Prog Mater Sci*, vol. 72, pp. 61–99, Jul. 2015, doi: 10.1016/j.pmatsci.2015.01.004.

Communication aligned with the Sustainable Development Objectives

11 SUSTAINABLE CITIES AND COMMUNITIES

13 CLIMATE ACTION

OBJETIVOS DE DESARROLLO SOSTENIBLE