energies

Review

Factors Influencing the Decision-Making Process at the End-of-Life Cycle of Onshore Wind Farms: A Systematic Review

João Agra Neto [1,2,*], Mario Orestes Aguirre González [1,2], Rajiv Lucas Pereira de Castro [3], David Cassimiro de Melo [2], Kezauyn Miranda Aiquoc [4], Andressa Medeiros Santiso [2], Rafael Monteiro de Vasconcelos [2], Lucas Honorato de Souza [2] and Eric Lucas dos Santos Cabral [1,2]

[1] Creation Group, Graduate Program in Petroleum Science and Engineering, Federal University of Rio Grande do Norte, Lagoa Nova University Campus, P.O. Box 1524, Natal 59078-900, RN, Brazil; eric.cabral@ufrn.br (E.L.d.S.C.); mariogonzalez@ufrn.edu.br (M.O.A.G.)
[2] Creation Group, Production Engineering Department, Federal University of Rio Grande do Norte, Lagoa Nova University Campus, P.O. Box 1524, Natal 59078-900, RN, Brazil; david.cassimiro.096@ufrn.edu.br (D.C.d.M.); andressa.santiso.014@ufrn.edu.br (A.M.S.); rafael.monteiro.050@ufrn.br (R.M.d.V.); lucashono14@gmail.com (L.H.d.S.)
[3] Department of Civil and Environmental Engineering, Federal University of Rio Grande do Norte, Lagoa Nova University Campus, P.O. Box 1524, Natal 59078-900, RN, Brazil; rajivlcastro@gmail.com
[4] Postgraduate Program in Public Health, Federal University of Rio Grande do Norte, Lagoa Nova University Campus, P.O. Box 1524, Natal 59078-900, RN, Brazil; kezauyn@gmail.com
* Correspondence: joaoagra_@hotmail.com

Abstract: It is observed that the number of onshore wind farms that reach the end of their service life is continually increasing. The decision-making process that defines the future of the farm is a challenge for the owners. This systematic review aimed to identify which factors influence the decision-making process at the end-of-life cycle of onshore wind farms. In accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol, a research strategy was developed and used the Scopus, Web of Science and EMBASE databases. Initially, 2767 articles were identified, but, after double-blind screening, 26 articles were analyzed in full. The scarcity of studies on this topic and little elucidation are limitations of this review. The results include (i) a systematization of six options for decision making, (ii) thirteen factors influencing the decision-making process associated with categories of external factors (logistics and infrastructure aspects, regulatory aspects and public policies, national energy guidelines, the technological development of the sector); and internal factors (economic/financial, operational and environmental aspects). It is concluded that most of the publications consist of simulations and theoretical studies highlighting a bottleneck in experiences and feasible data to support decisions at the end of service life. It is highlighted that most of the studies showed that partial decommissioning with partial repowering, as well as total decommissioning, were the most feasible options for the end-of-life cycle, with aspects related to public policies and regulatory aspects, as well as environmental, operational and economic/financial aspects, being the most influential, especially due to the wake effect, operation and maintenance costs (OPEX) and the protection of guarantees and incentives for operation in a new operating cycle.

Keywords: wind energy; onshore wind farm; end-of-life cycle; decommissioning; repowering; retrofitting; PRISMA; systematic review

Citation: Agra Neto, J.; González, M.O.A.; Castro, R.L.P.d.; Melo, D.C.d.; Aiquoc, K.M.; Santiso, A.M.; Vasconcelos, R.M.d.; Souza, L.H.d.; Cabral, E.L.d.S. Factors Influencing the Decision-Making Process at the End-of-Life Cycle of Onshore Wind Farms: A Systematic Review. *Energies* **2024**, *17*, 848. https://doi.org/10.3390/en17040848

Academic Editors: Abbas Mehrad Kazemi Amiri, Alasdair McDonald and Rebecca Windemer

Received: 26 September 2023
Revised: 17 November 2023
Accepted: 20 November 2023
Published: 11 February 2024

1. Introduction

From the 1990s onwards, with the possibility of the exhaustion of energy sources derived from fossil fuels, the risk of the destabilization of nations' economies due to the oil crisis, as well as problems related to climate change, drove the development of research and the adoption of renewable energies [1,2].

This promotion also generated a search for diversification and highlighted the need to complement energy matrices, especially in countries whose main sources were hydroelectrical plants and natural gas. From this perspective, the International Renewable Energy Agency (2020) shows that the share of renewable sources in energy generation will represent 28% in 2023 [3]. However, in the scenario projected for 2050, it could reach 86% of all energy produced, with emphasis on wind energy, which will represent 35% [4].

It is also observed that the projection of installed wind energy capacity will increase from 837 GW to 8000 GW in the next 28 years [4]. Furthermore, the Global Wind Energy Council (2022) points out that the installed capacity in 2021 came from onshore and offshore installations. In this scenario, onshore wind farms represent the largest production capacity, with 780 GW of the 837 GW produced by the two types of farms [4]. The expansion of the installation and activation of onshore wind farms has been occurring since the 2000s [5].

According to the Brazilian Wind Energy Association—ABEEólica (2023)—the Brazilian scenario follows this evolution profile. According to Infowind technical overview no. 30, there are 890 wind farms in commercial operation with an installed capacity of 25.037 GW [6]. Furthermore, in this evolution of installed capacity, it is possible to verify not only the increase in the number of current installations, but also those whose current status is in the construction phase and granted (with construction not started). Therefore, it is estimated that Brazil will reach the mark of 44.78 GW of wind capacity installed and in commercial operation in 2028 [6].

However, these wind farms have an expected service life of 20 to 25 years, making defining the final stage a challenge for several countries that have this energy source in their territory [7]. Ozoemena et al. (2018) and Wang et al. (2019) state that most of the first installations, in various parts of the world, are still in operation [8,9]. Therefore, information about the final stage of the life cycle, as well as the management of decision-making processes, is still scarce [8,9].

In this context, when observing the Brazilian reality, it is possible to see that the first onshore wind farms have already passed half of their contractual lives, entering the final phase of their projected service lives, which highlights the need to plan the decision-making process regarding the future of the wind farms. It is also worth noting that according to Law 14,182/2021, entrepreneurs can extend the term of the energy generation contract for onshore farms for up to 20 years [10].

According to the Brazilian Wind Energy Association (ABEEólica), in 2023, approximately 89 wind farms (10.1% of farms in operation) are at least half way through their service lives, with the end of their service lives expected to be in 2033. In 2038, it is estimated that this number will jump to 563 wind farms (63.8% of the total number of farms in operation) having gone through 75.0% of their service life, with the end of their service lives expected to be in 2043 [11].

The literature points to three possible scenarios in which the owner can choose for the future of the farm, which are decommissioning, the extension of service life or retrofit and repowering [12]. However, with regard to the final phases of the life cycle, studies still rely on assumptions, simulations or even exclude this phase in the analysis of their findings, which may be related to the lack of data and the systematization of successful strategies for its management [13].

Considering the growing need for studies and analyses related to the end-of-life cycle of onshore wind farms and the importance of the strategic decision to be taken, the following problem arises: What factors and variables influence the decision-making process at the end of the farms' service life in onshore wind?

Given this, the present study aims to identify the factors and possible variables influencing the decision process at the end-of-life cycle of onshore wind farms. Furthermore, this research presents other contributions, including the following:

- ❖ Carrying out a pioneering systematic review in relation to the factors and variables influencing the decision-making process at the end-of-life cycle of onshore wind farms;

- ❖ Presenting an overview of research that highlights the strategic decision at the end of the service life of onshore wind farms (Section 4.1);
- ❖ Identifying decision options at the end-of-life cycle of onshore wind farms.

This article is organized into five sections. After Section 1, with the introduction, Section 2 presents the Theoretical Background, and Section 3 describes the methodological approach. Section 4 presents a description of the systematization of factors identified in the literature. Finally, Section 5 presents the contributions of this study, final considerations, conclusions and recommendations.

2. Theoretical Background

Decommissioning consists of dismantling, decontamination and preparation for disposal, as well as the final disposal of the wind turbines and other components of the farm, so that legal requirements for safety and preservation or the recovery of the environment are met [14]. According to Hall, João and Knapp (2020), the decommissioning process can be divided into full decommissioning and partial decommissioning [15].

Total or complete decommissioning consists of the complete dismantling and removal of the farm, from intake structures to management environments and transmission cables. Furthermore, in this phase, the site is restored to its condition prior to the installation of the onshore wind farm, with the appropriate disposal of the parts, components and waste generated that can be reused, recycled and/or discarded [16–19].

The repowering process is related to the renewal of capture equipment, in which structures, such as wind turbines, are dismantled in order to replace them with more modern elements with a greater production capacity [20–22]. Repowering also has the possibility of being carried out partially in wind farms. Thus, there is a combination of partial decommissioning and partial repowering, as long as this alternative guarantees the best financial return for the company in relation to the investment and future return [15,21].

Retrofit is the maintenance of the main structure and remanufacturing/modernization of parts and components with the replacement of these elements, such as the generator, multiplier box, blades and steering or braking control mechanisms, among others [12,13,23,24]. Faced with these different scenarios, the decision-making process is a complex stage which highlights the need for technical and economic analysis to determine the best solution given the context and parameters determined by each company [25].

3. Methodology

In order to conduct this systematic review, the PRISMA Checklist guidelines were used [26]. Furthermore, the present review followed the methodology suggested by Yigitcanlar et al. (2019) and Regona et al. (2022), which is organized into three stages: (I) planning to develop the research aim, question and search criteria; (II) carrying out the review; and (III) scientific communication and dissemination [27,28].

In the first stage, review planning was carried out, in which the inclusion and exclusion criteria were listed, as presented in Table 1.

Table 1. Inclusion and exclusion criteria for selected documents.

Inclusion Criteria	Exclusion Criteria
Newspaper articles/journals	Duplicate records
Peer reviewed	Books, Book chapters, Theses, Dissertations and Technical Reports
Full text available online	Reports
Any language	Document published during conference
Relevance to the research aim	Not related to the research aim
End-of-life cycle of onshore wind farms	End-of-life cycle of other energy sources as well as offshore wind farms

Source: Prepared by the authors (2023).

In the second stage, carried out in June 2022, a systematic literature review was conducted following the PRISMA protocol without time or language restrictions. At this stage, the Scopus, Web of Science and EMBASE databases were electronically accessed without restrictions regarding the language of the articles or date of publication.

During the search for possible articles that could integrate or respond to the aim, the main keywords were identified. Therefore, the terms chosen to construct the search expression are shown in Figure 1.

("onshore wind farm" OR "wind farm" OR "wind energy" OR "wind power") AND ("life cycle assessment" OR "life cycle analysis") AND (decommissioning OR repowering OR retrofit OR dismantling OR "decision making")

Figure 1. Search Strategy. Source: Prepared by the authors (2023).

Studies published in books, theses and dissertations, conference reports, editorials, technical reports, government documents, industrial reports, non-academic documents or any other material that did not meet the inclusion criteria, as well as other literature reviews (integrative, narrative or systematic with or without meta-analysis), were not considered.

Initially, the results obtained from 2767 articles from databases were entered into the Mendeley Desktop® reference manager, version 1.19.4, to eliminate duplicate studies. Then, 2660 resulting articles were identified, which were exported to the Rayyan QCRI® software (https://rayyan.ai/reviews (accessed on 15 June 2022)) for screening by reading the title and abstract. Reading the titles and abstracts aims to filter the articles with elements capable of contributing to the answer to the guiding question, according to the criteria in Table 2.

Table 2. Article selection criteria.

Selection Criteria
✓ Onshore Wind Farms; ✓ End-of-Life Cycle; ✓ Decision at the end of service life; ➢ Deactivation of Commercial Operation (Partial or Full/Total Decommissioning). ➢ Extension of Service Life (Retrofit/Service Life Extension, Partial or Full/Total Repowering. ✓ Factors and Variables Influencing Studies, Analysis and Decisions at the End-of-Life Service of Onshore Wind Farms.

Source: Prepared by the authors (2023).

At the end of the previous stage, 101 studies were selected for full textual reading, still using the same software, in order to fully observe the relationship with the inclusion criteria. From this analysis, 26 articles (listed in Table 3) were obtained to be included in this systematic review and whose data were extracted to be assessed qualitatively and quantitatively. The complete systematic literature review process, following the PRISMA model, is illustrated in Figure 2.

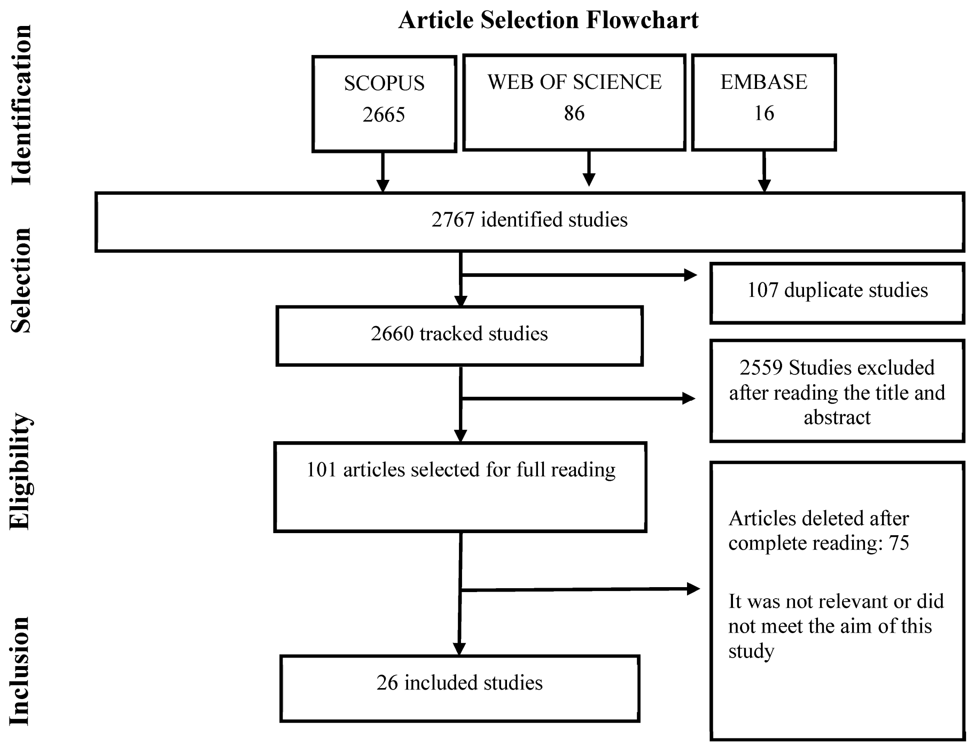
Table 3. Characterization of articles according to authors, year, location and journals of publication.

N	Authors	Year	Country	Journal
1	Martínez et al. [29]	2009	Spain	*International Journal of Life Cycle Assessment*
2	Martínez et al. [30]	2010	Spain	*Applied Energy*
3	Min, Lou and Wang [31]	2012	USA	*The Engineering Economist*
4	Cherrington et al. [32]	2012	United Kingdom	*Energy Policy*
5	Zhang et al. [33]	2012	China	*Computers & Chemical Engineering*
6	Ortegon, Nies and Sutherland [13]	2013	USA	*Journal of Cleaner Production*
7	Gervásio et al. [34]	2014	Portugal	*Engineering Structures*
8	Prabu and Sasi [35]	2015	India	*Wind Engineering*
9	Liu and Barlow [36]	2017	England	*Waste Management*
10	Sakellariou [37]	2017	USA	*Energy Systems*
11	Martínez et al. [38]	2018	Spain	*Renewable and Sustainable Energy Reviews*
12	Karoui et al. [39]	2019	Tunisia	*IEEE Transactions on Industry Applications*

Table 3. *Cont.*

N	Authors	Year	Country	Journal
13	Teffera et al. [40]	2020	Tunisia	*International Journal of Life Cycle Assessment*
14	Hall, João and Knapp [15]	2020	England and Scotland	*Environmental Impact Assessment Review*
15	Kitzing et al. [41]	2020	Denmark	*Nature Energy*
16	Pryor, Barthelmie and Shepherd [42]	2020	USA	*Scientific Reports*
17	Syed et al. [43]	2020	Pakistan	*Applied Energy*
18	Boopath et al. [44]	2020	India	*International Journal of Renewable Energy Research*
19	Bona, Espindola and Duran [45]	2021	Brazil	*Renewable and Sustainable Energy Reviews*
20	Rajaram, Krishnan and Guru [46]	2021	India	*International Energy Journal*
21	Khan et al. [47]	2021	Pakistan	*Applied Energy*
22	Volk et al. [48]	2021	Germany	*Resources, Conservation & Recycling*
23	Grau, Jung and Schindler [49]	2021	Germany	*Journal of Cleaner Production*
24	Jezierski, Mańkowski and Śpiewak [50]	2021	France	*Energies*—MDPI
25	Leite et al. [51]	2022	Brazil	*Renewable and Sustainable Energy Reviews*
26	Simón-Martín et al. [52]	2022	Spain	*Renewable and Sustainable Energy Reviews*

Source: Prepared by the authors (2023).



Source: Prepared by the authors (2023).

Figure 2. The PRISMA literature selection process.

The information from the studies was extracted and placed in the form of tables and charts, and then organized by the following topics: (a) reference of the article (authors, location, year of publication); (b) decision regarding the feasibility of the onshore wind farm at the end-of-life cycle; and (c) factors, types of factors and possible variables that influenced decision making.

In all stages of study selection, two reviewers (JAN and RLPC), trained to select studies, used analysis software and extracted studies and data, working independently. With the aim of guaranteeing the quality of the process, disagreements were resolved through a consensus. In cases where disagreements persisted, a third reviewer was requested to resolve the impasse (DCM). The studies referenced in the included articles were also analyzed to identify articles that met the inclusion criteria and for a timely additional citation.

4. Results and Discussion

4.1. Classification/Systematization of Publications

In this article, 2660 documents were found. After analyzing the inclusion and exclusion criteria, 26 articles were selected to compose the results, with a characterization in Table 3, published in scientific journals. While reading the documents, it was identified that there are still few studies that highlight the factors and variables influencing the decision-making process at the end-of-life cycle of an onshore wind farm.

These data coincide with the largest number of wind farms that are reaching the end of their life cycle, after 20 years or more of operation, especially in the European Union, the United States, India, China and Brazil [53]. Furthermore, authors point out a tendency for this scenario to increase between the years 2020 and 2030 [20], which highlights the importance of carrying out research on this topic in order to support the trajectory of verifying the feasibility of these farms at the end of the first life cycle.

The research shows that the topic, despite being new in the academic universe, presents recent evolution, with 16 studies between the years 2018 and 2022 [15,38–52], which represents 61.5% of the total studies published on the topic, with 3.9% in 2018 [38], 3.9% in 2019 [39], 23.10% in 2020 [15,40–44], 23.10% in 2021 [45–50] and 7.7% in 2022 [51,52]. The complete distribution of publications per year regarding the topic is presented in Figure 3.

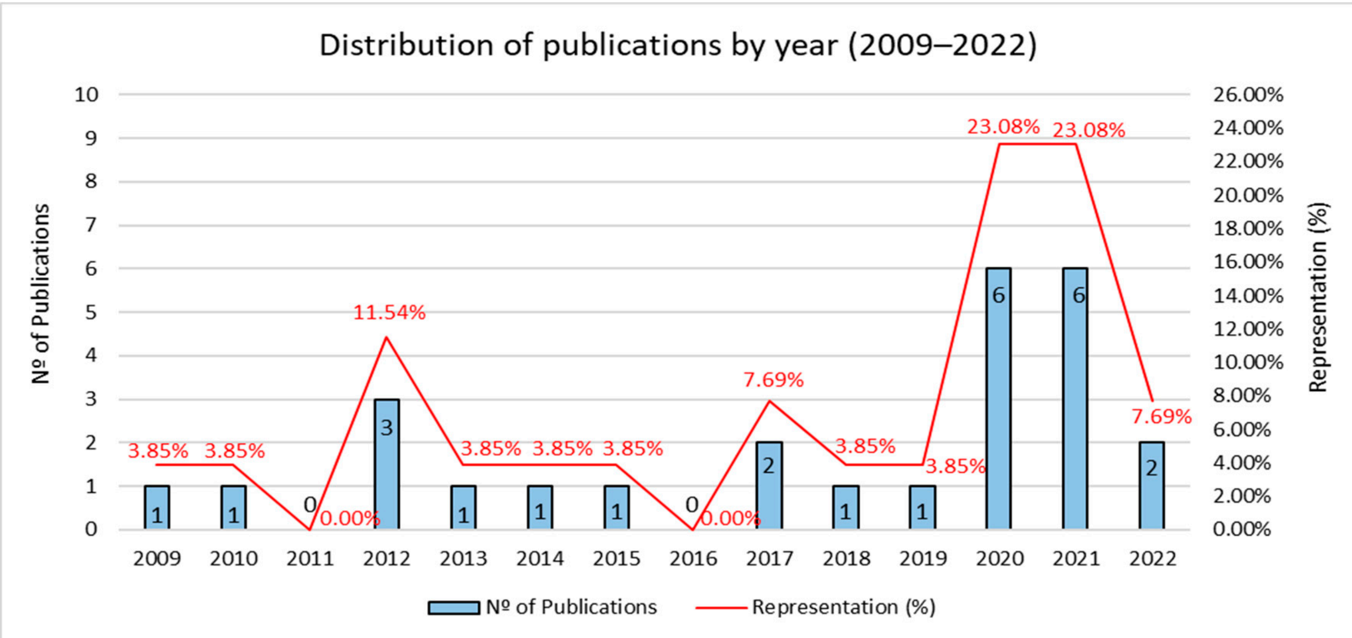


Figure 3. Distribution of publications by year (2009–2022). Source: Prepared by the authors (2023).

The analysis of publications by country reveals that the largest number of studies on the subject is concentrated in the United States (n = 4; 15.4%) [13,31,37,42], Spain (n = 4; 15.4%) [29,30,38,52], India (n = 3; 11.5%) [35,44,46], Germany (n = 2; 7.7%) [48,49] and Brazil (n = 2; 7.7%) [45,51]. The complete distribution of publications by country regarding the topic is presented in Figure 4.

It is worth noting that the countries where most of the studies were carried out can be directly related to those that make up the top 10 ranking countires in accumulated installed capacity of onshore wind farms in operation at the end of 2022, published by the Global Wind Energy Council—GWEC (2023) [54,55] (Table 4). This relationship highlights not only the leadership in the production of this energy source, but also a greater accumulation of farms near the end of their life cycle (service life). Still regarding this comparison, Pakistan stands out for being the only country with more than one study that does not make up the global ranking of the ten nations with the highest cumulative installed capacity [56].

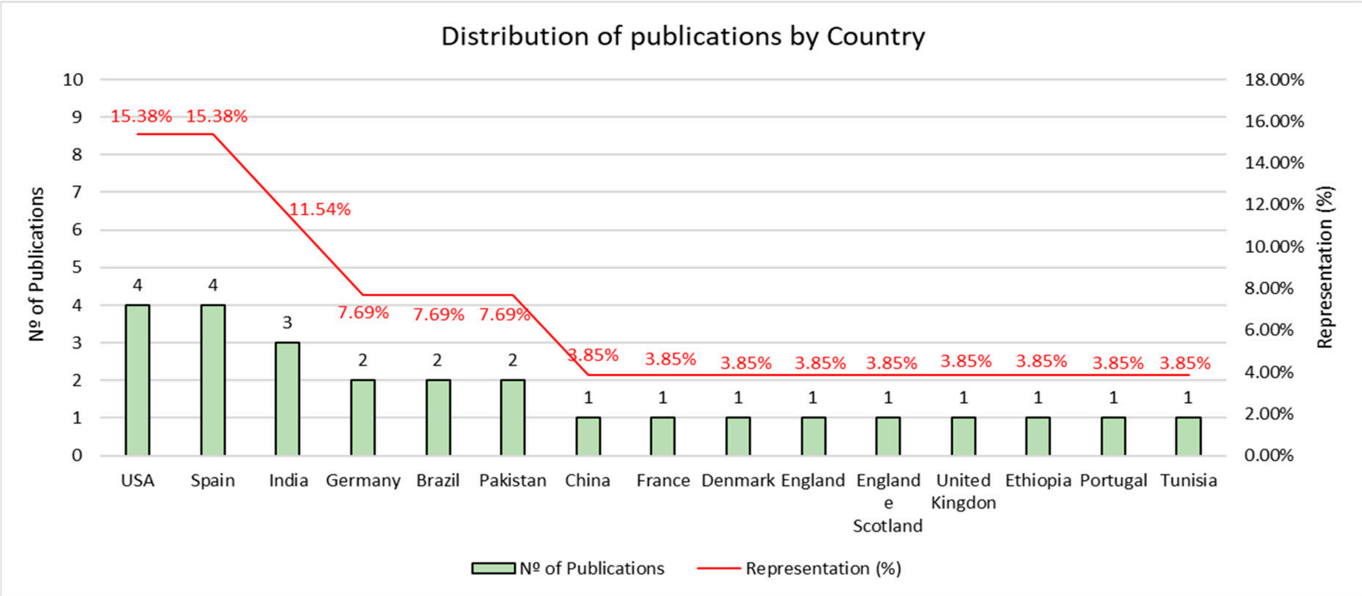


Figure 4. Distribution of publications by country. Source: Prepared by the authors (2023).

Table 4. Top 10 ranking in accumulated installed capacity by country (MW).

Ranking (Top 10)	Country	New Capacity Installed in 2022 (MW)	Accumulated Power/Installed Capacity (MW)	Representation (%)
1st	China	32,579	333,998	39.7%
2nd	United States	8612	144,184	17.1%
3rd	Germany	2403	58,951	7.0%
4th	India	1847	41,930	5.0%
5th	Spain	1659	29,793	3.5%
6th	Brazil	4065	25,632	3.0%
7th	France	1590	20,653	2.5%
8th	Canada	1006	15,261	1.8%
9th	United Kingdom	502	14,575	1.7%
10th	Sweden	2441	14,393	1.7%
Other Countries =		12,112	142,528	16.9%
TOTAL =		**68,816**	**841,898**	**100%**

Source: GWEC (2023) [55].

The analysis revealed that the 26 selected articles are distributed across 19 journals, of which only four (n = 4) have two or more publications on the topic, grouping 42.3% of these articles. The journals with the highest participation in publications on the subject are *Renewable and Sustainable Energy Reviews* (n = 4; 15.4%) [38,45,51,52], *Applied Energy* (n = 3; 11.5%) [30,47] and *The International Journal of Life Cycle Assessment* [29,40] and the *Journal of Cleaner Production* [13,49] with the same number (n = 2; 7.7%) [51,52] (Table 5).

Regarding the farm feasibility decision, ten (n = 10) studies pointed to partial decommissioning with partial repowering as one of the most feasible options [35,36,38,42,43,45,47,50–52], while seven (n = 7) studies indicated total decommissioning [15,29–32,37,48]. Another important finding was the possibility of partial decommissioning with repowering and the hybridization of the farm, having been identified in two studies [44,46] (Table 3).

The study by Martinez et al. (2010) analyzed that despite the good wind potential where the farm was located, the presence of agents that accelerated the corrosion process of the blades' elements, large temperature fluctuations and gusts of wind that caused blades to break converged on the decision of total decommissioning [30]. In this sense, Abadie and Goicoechea (2021) point out that when farms are close to the end of their life cycle, their failure rate increases considerably. However, it is not just the operating time that is the main factor in the aging of turbines and, mainly, the reduction in their performance [23]. There are other coefficients that lead to a drop in this performance, such as the location of a wind farm, weather and wind conditions, as well as the frequency of maintenance [23].

Table 5. Distribution of publications by journals and years.

Journal	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Total
Applied Energy	0	1	0	0	0	0	0	0	0	0	0	1	1	0	**3**
Computers & Chemical Engineering	0	0	0	1	0	0	0	0	0	0	0	0	0	0	**1**
Energies—MDPI	0	0	0	0	0	0	0	0	0	0	0	0	1	0	**1**
Energy Policy	0	0	0	1	0	0	0	0	0	0	0	0	0	0	**1**
Energy Systems	0	0	0	0	0	0	0	0	1	0	0	0	0	0	**1**
Engineering Structures	0	0	0	0	0	1	0	0	0	0	0	0	0	0	**1**
Environmental Impact Assessment Review	0	0	0	0	0	0	0	0	0	0	1	0	0	0	**1**
IEEE Transactions on Industry Applications	1	0	0	0	0	0	0	0	0	0	0	1	0	0	**2**
International Journal of Life Cycle Assessment	0	0	0	0	0	0	0	0	0	0	0	0	1	0	**1**
International Energy Journal	0	0	0	0	0	1	0	0	0	0	0	0	0	0	**1**
International Journal of Renewable Energy Research	0	0	0	0	0	0	0	0	0	0	0	1	0	0	**1**
Journal of Cleaner Production	0	0	0	0	1	0	0	0	0	0	0	0	1	0	**2**
Nature Energy	0	0	0	0	0	0	0	0	0	0	0	1	0	0	**1**
Resources, Conservation & Recycling	0	0	0	0	0	0	0	0	0	0	0	0	1	0	**1**
Renewable and Sustainable Energy Reviews	0	0	0	0	0	0	0	0	0	1	0	0	1	2	**4**
Scientific Reports	0	0	0	0	0	0	0	0	0	0	0	1	0	0	**1**
The Engineering Economist	0	0	0	1	0	0	0	0	0	0	0	0	0	0	**1**
Waste Management	0	0	0	0	0	0	0	0	1	0	0	0	0	0	**1**
Wind Engineering	0	0	0	0	0	0	1	0	0	0	0	0	0	0	**1**
Total	**1**	**1**	**0**	**3**	**1**	**1**	**1**	**0**	**2**	**1**	**1**	**6**	**6**	**2**	**26**

Source: Prepared by the authors (2023).

Therefore, total decommissioning is the last stage of the life cycle and may be related to financial and operational non-feasibility. This decision implies the total removal of above-soil structures, such as turbines and infrastructure, especially with the aim of recovering or restoring the land used [12,57].

In the research carried out in Tunisia, it was necessary to exchange fixed-speed turbines, which have lower nominal power, for variable-speed turbines. Furthermore, the authors state that the new turbines improve the stability of the electrical grid in the event of a voltage drop, due to the converters that act as static compensators during the failure, as well as generating an increase in the amount of energy and revenue, a reduction in maintenance costs and noise and layout optimization [39].

In this sense, repowering arises from the need to retrain a wind farm, since its production is unattractive from an economic and technological perspective. Furthermore, it is one of the alternatives to better take advantage of the farm's profitability, taking advantage of the initially planned project as well as the need to increase the performance and electricity production of the wind complex [58].

Technological evolution and reduction in maintenance costs can also influence the decision to exchange some old components for new ones, even before the farm reaches the end of its service life [20]. Furthermore, partial repowering can generate the partial decommissioning of some elements in order to improve production efficiency [24].

In this sense, a study carried out in India demonstrated an increase in the energy factor that was four times greater [59]. In turn, in Malpica, Spain, despite maintaining the nominal power prior to repowering, not only did the annual yield double, but the profitability also became satisfactory even in situations where there were no public subsidies [60].

Another alternative for extending a farm's service life, also known as retrofit, refers to a methodology that aims to modernize the existing turbine in a wind farm, in order to optimize control with automation, increase the plant's efficiency and extend its service life [24].

To this end, some elements of the turbine are exchanged, such as the gearbox and rotor blades, for more updated versions and/or turbine assembly with more modern control and electrical systems, unlike repowering, which is related to the complete replacement of turbine elements with more modern elements [24].

Regarding the hybridization of farms, in Tamil Nadu, located in India, Boopath et al. (2020) pointed out that strong solar irradiation during seven months of the year, better use of the wind density potential at higher heights, the presence of shadow-free regions due to the use of taller turbines, as well as the optimization of the layout and need, increasing capacity and yield, were fundamental factors for a farm's feasibility [44].

As for another hybridization experience, also in India, it was chosen due to the need to increase energy production, but with limitations on the use of occupied land [46]. Therefore, in addition to the use of more modern turbines with reduced noise emissions, it also reduced operational costs and increased the free space for photovoltaic plate installations, which enhanced the use of wind and solar resources in the region and optimized the use of limited space [46].

Furthermore, it is worth highlighting that of the 26 articles, only five dealt with factual experiences. The other 21 surveys deal with estimates or expectations of possible decisions in real scenarios (Table 6). For Ortegon et al. (2013), in addition to there being little research on the end-of-life cycle of wind turbines, in the literature, it is possible to identify a predominance of studies presenting assumptions or incomplete data in the results, especially regarding successful experiences [13]. This may indicate not only the lack of expertise in assessing the decision-making process, but also highlights the worrying lack of studies on the subject, especially given the urgent approach to the end-of-life cycle of onshore wind farms belonging to the main wind-energy-producing countries of the world. Therefore, it is observed that the simulations found in the studies in this review constitute an emerging attempt to address this constraint.

Table 6. Quantity of studies by continent, methodology and decision.

Continent	Number of Studies	Empirical	Theoretical	Decision					
				Full Decommissioning (Deactivation)	**Total Decommissioning with Full Repowering**	**Partial Decommissioning with Partial Repowering**	**Partial Decommissioning with Retrofit**	**Partial Decommissioning with Repowering and Hybridization**	**Partial Decommissioning with Repowering and Retrofit**
North America	04	0	04	02	01	01	00	00	00
South America	02	0	02	00	00	02	00	00	00
Africa	02	02	00	00	01	00	01	00	00
Asia	06	01	05	00	00	03	01	02	00
Europe	12	02	10	05	02	04	00	00	01
TOTAL	26	05	21	07	04	10	02	02	01

Source: Prepared by the authors (2023).

4.2. Classification of Categories

In the data and information extraction stage, the factors influencing decision making at the end-of-life cycle of onshore wind farms were identified and subsequently categorized. These categories were defined according to the similarity of the factors found, which resulted in seven categories (Appendix A—Table A1).

The categories were divided according to their origin, being the categories with external aspects and the categories with internal aspects. The external-aspect categories were defined based on external factors which are associated with national energy planning; legislations; normative issues; physical and electrical infrastructure; and improving the efficiency and effectiveness of the technology used. The categories with internal aspects were classified based on internal factors that are related to the operation, conditions and situation of the farm. This categorization was defined as follows:

- ❖ Categories with external aspects:
  - ➢ National energy guideline (national aspect);
  - ➢ Regulatory aspects and public policies;
  - ➢ Logistics and infrastructure aspect;
  - ➢ Technological development in the sector.
- ❖ Categories with internal aspects:
  - ➢ Economic/financial aspect;
  - ➢ Environmental aspect;
  - ➢ Operational aspect.

Figure 5 demonstrates the forces of influence between the categories and factors identified in the articles of this systematic review and their relationship in the decision-making process at the end of the onshore wind farm's life cycle. These are classified as follows:

- ❖ The strong-influence arrow refers to the relationship between the categories with external aspects of factors not controllable by the farm entrepreneur and which are decisive for the legitimacy, standardization of operation, availability of infrastructure and production chain—green arrows;
- ❖ The intermediate/medium-influence arrow refers to the relationship between categories with uncontrollable external factors that interfere with categories of controllable internal factors—yellow arrows;
- ❖ The weak-influence arrow refers to the relationship between the internal-aspect categories and the internal factors that are controllable by the farm entrepreneur—blue arrows.

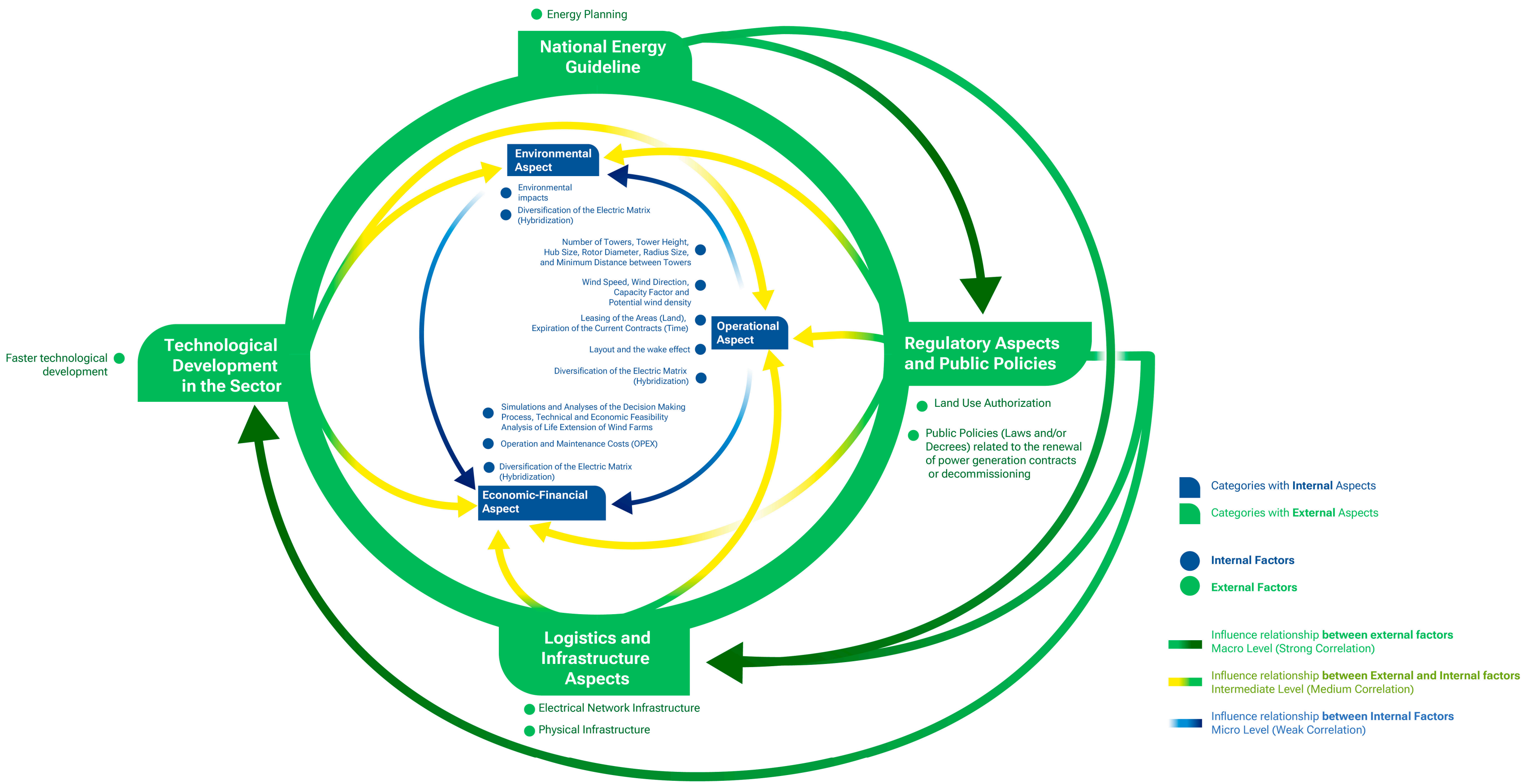


Figure 5. Categories, factors and aspects present in the decision-making process to deactivate or extend the operational service life of an onshore wind farm. **Source:** Prepared by the authors (2023).

In this research, it was possible to observe that the categories with external aspects were highlighted as a starting point in the feasibility analyses, since they are related not only to the insertion of a wind farm to meet the goals of national energy planning, but are also fundamental for the generation of subsidies in order to promote the continuity of the farm [13,31,32].

Furthermore, the category referring to the logistics and infrastructure aspect was related, for example, to the electrical network and external physical structure for transporting farm components. In turn, the sector's technological development category was related to research and the technological evolution of the wind industry. Therefore, the strong relationship between these two categories was evident, mainly due to the obsolescence of old elements, as well as the adoption of new parts with greater power and reliability, which have larger dimensions, making it essential to assess this external structure in the decision-making process [38,39].

After highlighting the external aspects, it was observed that these reverberate in the internal-aspect categories (environmental, operational and economic/financial aspects), as shown in Figure 5.

4.2.1. Categories with External Factors

National Energy Guidelines (National Aspects)

The first category identified from the systematic review was national energy guidelines. This aspect brings together variables from the national aspects that are associated with the decision-making process, the most predominant of which are the following:

(a) Energy Planning

National energy guidelines define paths and establish strategies for achieving the goals set out in the national plan, as well as the agents involved, such as government, business and society bodies [61]. Based on decisions made by senior government management, the chain of administrative acts and processes that allow for the organization and regulation of the nation's electrical system is defined. In this sense, the guidelines enable and guide the energy functioning, bureaucratic means and operational control of the electrical network [61,62].

Therefore, in this study, it was found that the category of national energy guidelines is interconnected with the category of public policies and regulatory aspects, as it points to the chain for the implementation, execution and control of the actions outlined in the planning for the development of the energy matrix and electricity, which can guide the decision-making process at the end of the farm's life cycle.

Studies carried out in Germany highlighted the need for greater energy production, especially from wind farms, in recent years. This led to a greater number of decisions to repower or decommission farms in operation in the country [48,49]. Nonetheless, it is observed that in the long term, repowering in isolation will not be able to generate the essential stability for the supply of wind energy, since the increased rigor of the Geographical Restrictions Law, which determines a minimum spacing between the turbines, as well as the limitation on installing larger rotors and blades, constitute barriers to the continuity of the farm [49].

Therefore, in addition to making the adoption of gigantic structures in regions that have reached their maximum wind capacity counterproductive, the environmental impact generated goes against what is determined by local legislation, especially regarding the generation of waste in the dismantling process [48].

Energy planning, in addition to presenting the need for energy diversification and increasing its generation, can highlight the analysis of the electrical network to drain the energy produced. Therefore, knowledge of the energy-production capacity of each source available in the territory allows the execution of good energy planning, as well as subsidizing the continuity of the farm. Studies carried out in Tunisia [39] and India [46] demonstrate that the choice of more technological elements improved the stability of the electrical grid, as the installed converters compensate for production failures, reducing voltage drops [39] in the turbines. The most modern systems have improved the integration of the electrical grid and have complied with the standards required in their country [46].

In India, with the directive to promote the increase in the participation of wind sources in the electrical matrix, through the Ministry of New and Renewable Energy (MNRE), promotional policies were created, which boosted the development of renewable capacities and the installation of state-of-the-art wind turbines. With the advancement of wind technology, the onshore power generators available today have a rating of 2000 kW to 3000 kW and a service life of wind turbines of approximately 25 years. Therefore, the advantage of repowering in the study was the removal of a large number of small-capacity wind turbines, to install fewer turbines with greater power [46].

In the United States, the most cited public policy that is related to national guidelines is the execution of contracts and assignment of land for the installation of onshore wind farms [13,31,37,42]. Despite the differences highlighted regarding the renewal of incentives in the North American territory [37], the places that tend to continue promoting subsidies can boost the permanence of energy investment through the repowering of the project [13]. On the other hand, the Brazilian study shows that one of the negative results of the lack of national prioritization in subsidizing repowering and life extension strategies is the consequent definitive mass decommissioning of wind energy, both locally and around the world [51].

Public Policies and Regulatory Aspects

The second category identified from the systematic review was public policies and regulatory aspects. This aspect brings together variables from aspects that are associated with the decision-making process, the most predominant of which are as follows:

(a) Land-use authorization;
(b) Public policies (laws and/or decrees) related to the renewal of power generation contracts or decommissioning.

The decision at the end of the onshore wind farm's life cycle is a complex issue with several aspects and factors involved. As highlighted in the previous section (National Energy Guidelines (National Aspects)), public policies and regulatory aspects are fundamental in the decision-making process.

Despite pointing out the conceptual multiplicity of public policies, Stuckert (2015) explains that it is a set of interconnected decisions, based on the interests of national planning or management, which involve the selection of aims and the methods necessary to achieve them, in addition to being able to generate organizational processes, grant benefits and collect taxes. In this context, regulatory policies are forged in a predominantly pluralistic scenario, in which the relationship between different actors, their influence and interests play a crucial role in the ability to approve a particular policy. This aspect, in turn, has the purpose of defining and regulating standards [63].

Based on its guidelines and political decisions regarding energy generation in each country, one of the main factors identified were subsidies and political incentives in order to encourage the insertion of other non-governmental actors in energy production. The following are among those presented:

- ❖ Encouraging the energy transition as a result of the aim to reduce the use of fossil fuels and pollutant emissions [33,45];
- ❖ Incentives under the country's renewable energy sources law [37,45,46,48,51];
- ❖ Attractive political and financial subsidies and incentives for continued operation [13,31,42,51];
- ❖ Guarantees to protect investments against the reduction in the average value of market clearing prices and the increase in their volatility [52];
- ❖ The duration of contracts, renewal criteria and obligations of energy generators [13,31,42,51];
- ❖ The renewal and validity of licenses to operate the farm [13,31,45,48].

From this perspective, the research shows that public policies and regulatory aspects were cited not only as an aspect that promotes or limits the insertion of wind farms in energy generation, but also in the continuity of operation, even after 20 years. In a study that aimed to analyze public policy instruments for the development of wind farms in Poland, it was pointed out that regulations are considered during assessment and decisions for wind investment and can generate infrastructural changes in the supply chain [64]. The authors also highlighted the positive impact on the growth of this sector when there is legislative stability and the emergence of the wind sector is met [64].

Studies carried out in the United States [13,31] and Spain [52] indicate that the granting of licenses, the continuity of subsidies and political incentives were directly associated with the decision to repower and/or decommission a farm. Ortegon, Nies and Sutherland (2013) also highlight that when these benefits expire, leasing the land used at an attractive price is an important factor in the decision to repower the farm.

According to Min, Lou and Wang (2012), it is interesting to investigate the conversion of the initial subsidy to the maintenance and operation (O&M) subsidy. Currently, the O&M cost subsidy differs from the production tax credit (PTC) used in the United States, as the PTC is advanced only for the first few years, assuming that a portion of the tax is paid to the government. Furthermore, it is recommended that the government presents environmentally conscious purposes that aim to avoid a premature exit from the farms, based on the renewable site structure, and also encourage the entry of new companies into the renewable energy market [31].

In Brazil, authors indicated that changes in the requirements to receive discounts on the transmission system usage tariff and the distribution system usage tariff for producers of alternative sources of up to 30 MW could be beneficial for the sector, as they can stimulate the choice for repowering [45]. A study carried out in Germany indicates that the remuneration guaranteed by the renewable energy law will cease to be in force after 20 years of operation of a wind turbine [49].

Other increments identified were the minimum floor policy for the payment of energy produced, remuneration through carbon credit titles or efficiency awards [52]. On the other hand, a study on the effectiveness of the Italian government incentive mechanism showed contributions in guaranteeing the final price of energy sales; however, the bureaucratization and lack of standardization of the administrative process in European Union countries puts the success of the project at risk [65].

In addition to these direct economic incentives, it is important to highlight that indirect incentives, such as the guarantee of minimum acquisition prices, in order to protect the fair remuneration of invested capital in the face of market volatility, were characterized as attractive to investors, especially given the repowering process in which the prices of new parts can be defining elements for this decision [52]. In this sense, encouraging the local production of wind equipment can generate stability in prices and product supply and, thus, benefit the entire production chain of the country's wind industry [66].

The strong influence of public policies and regulatory aspects is also evident in the process of decommissioning a wind farm with full or total decommissioning, when legislation defines the criteria for waste disposal, the application and exemption imposed for waste treatment [48,67]. Therefore, well-defined federal and state legislation on the end of service life of a wind farm is extremely important to guide the responsibilities and obligations of energy-generating companies in relation to the removal of equipment and site restoration [38,48] in order to also reduce the risk of abandoning the project without correct deactivation [13].

Authors also point out the relationship between investment capital and public policies, in which governments can impact the service life of wind farms through the application of or reductions in tax charges and initial investments, as well as during operation [31]. In this sense, the government can configure itself as an agent controlling the number of energy-producing companies and the country's renewable energy market.

Research carried out in California, USA, also shows that the preparation of prior studies in the case of decommissioning is included as a requirement for granting construction licenses for the farm [37]. These studies consider the type of decommissioning equipment, mobilization costs, the type of material that would be discarded and its transportation costs, as well as the disposal of materials with incineration or landfill, which material would be recovered, for example, steel towers, and their recycling costs [37].

According to WindEurope (2020), in countries like Denmark, Ireland and the Netherlands, there are laws and regulatory standards that indicate various conditions to be met in the decommissioning process, and even taxation. In Spain, there is no regulatory framework on the decommissioning of wind turbines, but requirements are included in the environmental impact assessment (EIA) for each project [68].

In the UK, the Electrical Works Regulations state that the competent authority must not grant the application unless an environmental impact assessment has been carried out, and these regulations are based on EU Directive 2014/52, which states that information for the EIAs must include a description of the project's likely significant effects on the environment, including demolition work [32]. However, it is not clear whether the term "demolition" also applies to "decommissioning". Brazilian legislation is far from these other countries, as it uses the law created for oil exploration, and the Ministry of Mines and Energy still does not efficiently regulate this sector [45,51].

Logistics and Infrastructure Aspects

The third category identified from the systematic review was logistics and infrastructure aspects. These aspects bring together variables from aspects that are associated with the decision-making process, the most predominant of which are the following:

(a) Electrical network infrastructure;
(b) Physical infrastructure.

The category of logistics aspects and infrastructure encompasses two important pillars. The first pillar refers to the physical infrastructure responsible for allowing the transport (roads and access) of the materials necessary for the maintenance and modernization of the farm and the storage of equipment, as well as the availability of qualified labor to carry out the activities in cases of the extension of service life [46,52]. In the case of deactivation and dismantling due to the exchange of parts, the same infrastructure and logistics will allow the transport of parts, components, wind turbines and waste (scrap) for proper treatment [15,37,41].

The second pillar of this category is related to electrical energy transmission infrastructure. It was observed in the studies that for the decision or in the simulation of extending service life, they pointed to integration with the electrical grid as a key point for the continued operation of the farm, since most of the projects needed to increase their capacity, consequently ensuring a stable network for energy transmission [39.50]. In cases of deactivation, there will be greater availability of energy flow capacity in a given transmission network.

Authors also showed that the main factors related to the logistics aspect and the process of repowering or extending the service life are related to the possibility of using the area of an existing wind farm, the new interferences in the environment of other locations, in addition to increasing the energy yield in areas where it is impossible to expand land use [49,58,68]. In India, it was observed that the adoption of more modern turbines generated better integration and compatibility of machines with the electrical grid and an increase in energy generation without the need for additional land [46].

On the other hand, a study carried out in France that identified interdependence between repowering and the logistics aspect pointed out that the replacement of elements with more efficient ones was associated with an increase in logistics costs, since these new elements with greater production possibilities are longer and heavier [50]. As a result, in the process of repowering the Treffendel wind farm, there were savings in production costs due to logistics activities, which made it possible to restore the farm and increase its energy-production capacity by an average of 15%, representing an energy production of around 21.28 GWh/year, with the farm's service life increasing to 25 years [50].

Adequate infrastructure for road, rail and sea transport installed close to the projects is essential and helps to reduce costs [50]. Logistics support must be present from the moment of investment, the construction of a wind farm, the operational system and even the maintenance and decommissioning process, thus being essential to optimize operations and reduce unnecessary future expenses [69]. Furthermore, indirectly, the presence of these wind farms can also add social benefits, since local transport and traffic conditions are often improved [70].

The intermediate correlation between the internal economic/financial and operational aspects was verified in the study carried out in Spain, in which the reconfiguration to mitigate the wake effect generated between the wind turbines in the internal part of the project and among other existing farms generated concerns about the inability of the electrical network to evacuate the energy generated due to the increase in its nominal power [52].

Ortegon et al. (2013) point out that the advantages in repowering are related to improving power density because the production per unit area is increased, the number of units is reduced, efficiency is improved and opportunities derived from existing infrastructure can take advantage of network connections and historical operation. This reduces logistics costs compared to the construction and development of a new wind farm, as well as avoiding a new bureaucratic process, such as land, environmental and archaeological regularization [51].

Technological Development in the Sector

The fourth category identified from this systematic review was technological development in the sector. This aspect brings together variables from aspects that are associated with the decision-making process, the most predominant of which are the following:

(a) Faster Technological Development

The technological development aspect in the sector involves research, development and innovation associated with the evolution of wind elements, especially wind turbines. This evolution allows the replacement of old wind turbines with models with more added technology, with greater efficiency and nominal power [36,39]. This evolution allows for gains in scale and a reduction in the number of towers while maintaining the installed capacity, or the same number of towers with a greater installed capacity [38.46]. As a result, the project generates more energy, taking advantage of investments already made without the need to increase operating costs by leasing new areas [13,38].

Furthermore, the aforementioned increase in energy generation from new wind turbines allows for the consumption of less reactive power, which is related to the energy that is lost during transmission and distribution, in addition to presenting greater compatibility with the grid due to meeting the requirements of the network code [46], which highlights the correlation with the logistics and infrastructure aspects. Martinez et al. (2018) further state that the network, the original substation and the transport-related infrastructure must be considered in any modification and repowering process [38].

In a review of the technological evolution of onshore wind turbines, authors demonstrate that this evolution is not only limited to cost reduction and increased blades and nominal power [71], but also incorporates innovations that minimize environmental impacts and social impacts and that meet the conditions and specificities of the projects and the network, in addition to developing improvements for foundations, installations and maintenance, which emerge as a new profitable market opportunity [71].

From this perspective, authors point out the importance of adopting regulatory and incentive strategies as a national investment for research and technological development in the sector, in order to meet energy production goals and strengthen the country's wind industry, thus generating more energy stability as well as of the local market [72,73].

A study carried out in India showed that the country already has extensive experience with wind energy and that the government has a repowering policy for sites with old wind turbines [46]. In another Indian study, it assesses that despite advances in the production of wind elements with the implementation of the country's wind technology center and government incentives, foreign technological dependence and lack of qualified labor constitute a bottleneck for full sector development [66].

In Brazil, there have been farms in operation for more than ten years, and in new markets, the end-of-life strategy is not well discussed and established, despite being an urgent factor for the coming years [51]. Accordingly, there is a clear need to expand the discussion on innovation policies in wind energy, as well as for other renewable sources. In this sense, the promotion of technological policies in Brazil needs to be carried out through instruments to encourage and promote research into wind energy and improvements in its production.

In the study carried out in Tunisia, in which the performances of new wind turbines and their impacts on the electrical grid were compared with old wind turbines, it was evidenced that the new turbines guaranteed greater stability and reliability of the electrical grid, reducing voltage drops due to converters acting as static compensators during failure and requiring less maintenance [39]. Another point of improvement highlighted is the possibility of generating energy even at low wind speeds. Therefore, 1.25 MW was produced with wind speeds of 2 m/s, while the old turbines produced 150 to 250 KW with winds of 5 m/s [39].

In turn, the relationship between the technological development aspect of the sector and the operational aspect is evidenced in studies when, in the decision-making process, there is the need to change the layout, the wear of wind elements, and especially the need to increase energy production with or without limitations due to regulatory aspects and public policies. From this perspective, in Germany, the installation of taller towers makes it possible to increase energy capacity, despite geographical expansion restrictions [49].

In the study carried out in England, when they identified wear on the elements of the towers, especially on the blades that had been in operation for 17 or 18 years, they assessed that the decision to extend the service life without changing these parts would require major repair work. On that occasion, they verified that partial repowering with more efficient and technological blade installations would meet the production need, with an increase in scale, power and, consequently, blades [36].

In studies that presented hybridization as an option for the maximum use of land due to a reduction in the number of towers and the emergence of corridors with an interesting incidence of solar radiation, it brings to light an indirect benefit of technological improvements in wind elements, applied in the process of repowering.

As a result, the installation of taller towers and solar panels in these corridors increased the capacity from 1.8 MW to 4 MW from 1.8 MW in Kayathar, India [46], and in Tamil, India, enabling greater use of the wind potential at higher heights, layout optimization, better use of the existing network and logistics infrastructures, as well as increased capacity and yield [44]. Prabu and Kottayil (2015), when assessing the technological development of Kayathar wind farms in Tamil Nadu in India, corroborate these studies by demonstrating that as of 2013, energy production was approximately 20,150 MW thanks to the use of high-technology machines, innovation and efficiency, allowing us to take advantage of the benefits of wind [35].

Regarding the correlation between the technological development aspect of the sector and the environmental aspect, studies also demonstrated the improvement of materials in the composition of wind elements in order to reduce environmental impacts at the end-of-life cycle, such as increasing the recycling rates and improving the disposal process [34,37,40,48]; reducing human and territorial toxicity [40]; and compensating for environmental impacts generated in manufacturing, operation and maintenance [29].

As for the correlation with the economic/financial aspect, all studies cited that costs are a factor considered in the decision-making process at the end of a farm's life cycle. In repowering simulations of the Dois Riachos wind farm, it was observed that 2.0 MW turbines at a height of 100 m demonstrate good performance, surpassing 3.0 MW models. This finding shows that turbines with lower powers, at greater heights, can perform energy generation satisfactorily and reduce costs [45].

In addition to repowering, the process of remanufacturing wind turbines was also considered as a relevant technology for the wind energy generation market, which is an alternative to managing the end of use of a previously unexplored product. In this process, there is the opportunity to reduce the consumption of virgin raw materials, preserving embodied energy and reducing carbon production resulting from new installations [13]. However, it is worth highlighting that the cost and success of remanufacturing directly depend on the ways in which recovery and reprocessing activities are carried out, with a complex relationship between cost, quality, performance, operation/maintenance, technologies used and market interest [13].

4.2.2. Categories with Internal Factors

Economic/Financial Aspects

The fifth category identified from the systematic review was the economic/financial aspects. This aspect brings together variables from economic/financial aspects that are associated with the decision-making process, the most predominant of which are the following:

(a) Investments (CAPEX)/ capital cost;
(b) Operation and maintenance costs in relation to operational output (OPEX):
   i. Obsolete parts resulting in a decrease in total power generation and an increase in operation and maintenance costs (OPEX);
   ii. Unsuitable location (presence of degrading agents, causing accelerated depreciation) and higher maintenance costs (OPEX);
   iii. Expiration of land-leasing contracts for wind farms;
   iv. Leasing time and land-use authorization;
   v. Possibility of reducing the number of towers and the operation and maintenance cost (OPEX).
(c) The price of the new wind generator in the case of full repowering;
(d) Disposal and dismantling costs including labor and equipment and transportation;
(e) Removal and/or reuse cost;
(f) Material residual value, recycling costs and disposal costs.

In this context, the life cycle cost (LCC) technique is the technique that seeks to relate the costs involved in the service life of a wind farm with its life cycle phases, considering, at each stage, the different economic impacts [74–76].

According to the Irish Wind Energy Association—IWEA (2019)—expenses (costs, expenses and investments) are distributed throughout the life cycle of an onshore wind farm and its seven stages (feasibility, planning and authorization, pre-construction, construction, commissioning, operation and decommissioning), from design through to acquisition, construction, operation, maintenance and final disposal [77]. Therefore, the cost elements of a wind farm are categorized into CAPEX (capital expenditure), OPEX (operational expenditure) and DECEX (decommissioning expenditure) [12,78], as shown in Figure 6 and Table 7.

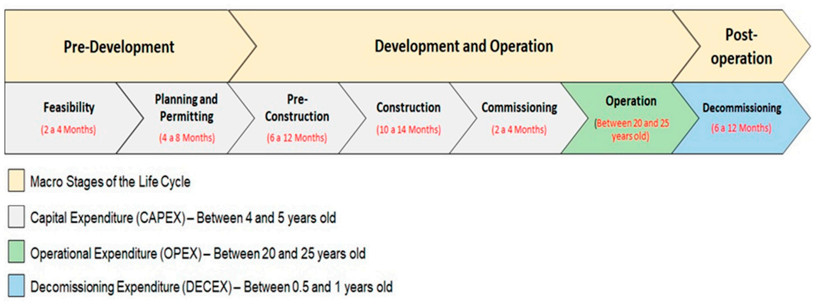


Figure 6. Classification of expenses by type of category in relation to the life cycle phases of an onshore wind energy plant, Source: Adapted from the Irish Wind Energy Association—IWEA (2019).

Table 7. Components of the life cycle costs of an onshore wind farm.

Project Phase	Definition	Components
Feasibility	Refers to the time it takes to identify suitable locations for constructing a wind farm.	❖ Location identification costs; ❖ Costs for assessing the site's wind potential.
Planning, licensing and authorization	The withdrawal of the necessary licenses to make a wind farm feasible.	❖ Costs for feasibility studies and analyses (technical, economic and environmental); ❖ Project management costs; ❖ Costs related to leasing negotiations and area concessions (lands); ❖ Costs with legal authorizations.
Pre-construction	Construction planning and negotiation of an energy sales contract are carried out.	❖ Negotiation costs for construction contracts; ❖ Costs with engineering activities; ❖ Contingency costs.
Construction	Phase in which civil works, electrical infrastructure and wind turbines are brought to the installation site.	❖ Investments in acquisition and manufacturing of parts and components (turbines, blades, nacelle, others); ❖ Transportation costs to the construction site of contractors, civil works, electrical infrastructure and wind turbines; ❖ Costs for construction of local roads/improvement of public roads; ❖ Costs for constructing foundations; ❖ Costs for implementing the electrical substation, energy collection and transmission system; ❖ Costs for the construction and assembly of transported wind components.
Commissioning	The checking, testing and adjustments of equipment until it is ready to operate safely and reliably.	❖ Costs for testing and adjusting a wind farm; ❖ Commissioning costs; ❖ Insurance costs.
Operation	Operational phase of the project, in which the farm produces electrical energy from wind energy and is sold.	❖ Administrative costs; ❖ Security and insurance costs; ❖ Costs for leasing areas (rent); ❖ Costs for preventive (proactive), predictive and corrective maintenance.
Operational Deactivation	This is the deactivation of the farm, at which point the plant reaches the end of its service life.	❖ Costs for feasibility studies and analyses (technical, economic and environmental); ❖ Decommissioning costs; ❖ Waste management; ❖ Site cleaning; ❖ Post-decommissioning monitoring.
Service Life Extension (may or may not exist)	A reinvestment to extend the service life and operation of a wind farm.	❖ Costs for feasibility studies and analyses (technical, economic and environmental); ❖ Decommissioning costs (partial or total); ❖ Waste management; ❖ Reinvestment.

Source: Adapted from [12,77,79].

The CAPEX represents all acquired assets, such as the costs of the turbine, blades, tower, transformer, foundations, site preparation, grid connection, unforeseen events, substations and connection to distribution [12]. According to Varella Filho (2013), high values in the CAPEX calculation may indicate production chains with low efficiency, while lower values indicate a more efficient and effective system. Therefore, when analyzed individually regarding the feasibility of a project, low values indicate the feasibility of the investment [80].

Operation and maintenance costs (OPEX) reflect all capital spent on operation, materials, maintenance and labor, with the aim of expanding the service life of the plant in order to optimize production when necessary [79]. In a company in the wind sector, OPEX is reflected in all maintenance carried out on equipment, the costs of replacing parts, and all inspection and monitoring services necessary for full operation [81].

As for OPEX, maintenance costs are influenced, in some cases, by the use of obsolete parts and/or the inappropriate location of a wind farm, justified by the existence of degrading agents that can lead to accelerated depreciation of the entire wind farm installation, causing a greater number of maintenance and/or replacements of these parts and components, negatively resulting in an increase in operation and maintenance costs (OPEX), as well as a decrease in energy production [34,51].

Another important factor to be discussed is the issue of leasing areas, which is influenced by the expiration of land-leasing contracts and competitiveness for the best areas (with the greatest known wind potential). Associated with fundamental points, such as leasing time and land-use authorization, they can increase leasing costs in contract-renewal negotiations and the acquisition of new contracts, in situations of area expansion [13,82]. On the other hand, in cases of total or complete repowering, the possibility of reducing the number of towers leads to a reduction in OPEX [51].

Decommissioning expenditure (DECEX) is related to the costs related to decommissioning, present in the deactivation and dismantling of a wind farm's capture structures at the end of its operations and/or the end of the concession period, and there may be reuse or recycling of the elements that composes it [83,84].

Regarding the residual value and removal and reuse cost, Gervásio et al. (2014) show that the percentage of material that will be reused is related to cost reduction in the process of total decommissioning or partial repowering with partial decommissioning [34]. Added to this, the remanufacturing process of the blades and other elements can be both reused in the farm and also resold to emerging countries in Latin America, Africa and some Asian countries.

The number of examples that study and analyze this topic and the advantages and disadvantages in relation to decommissioning and extending the service life of onshore wind farms is very limited. Welstead et al. (2013) [57] present estimates of the costs and revenues related to the possibility of decommissioning and restoration (extension of service life) in case studies in the United Kingdom and the United States, presented in Table 8.

Table 8. Deactivation and restoration costs.

Wind Farm	What Does It Cover?	Cost Estimation	Revenue Estimate
Whitelee Wind Farm	Removal of turbines, upper level of foundations, tracks, cables, substation, associated constructions and expansion of the visitor center for future use.	GBP 23,000/turbine, GBP 4651/blade recycling turbine, GBP 7938/turbine foundation, GBP 3761/track turbine, GBP 10,027/turbine cable removal, GBP 60,000/substation, associated constructions, visitor center improvement.	GBP 78,690/turbine (resale of steel, copper, cast iron) Positive balance estimated between GBP 3 million and 8.1 million.
Carraig Gheal Wind Farm	Removal of all turbines and associated electrical components, turbines split on site, bases 1.0 m deep, buried cables left on site, cut and filled above soil.	GBP 300 tonnes/turbine estimate. Estimated total cost between GBP 27,438 and GBP 548,778/turbine (including scrap value and inflation).	GBP 200/tonne scrap value.
Gwynt y Môr Ltd. Offshore Wind Farm	Removal of installations, waste management, inspections, monitoring, maintenance and management where the installation is not completely removed.	GBP 400,000/turbine. Decommissioning fund estimated at GBP 106 million to be placed in escrow account (10/year).	Not estimated.
New Grange Wind Farm	Removal of towers, bases (48-inch depth), removal collection system, seeding and revegetation.	Gross cost—USD 88,955/turbine. Net cost—USD 53,955/turbine.	USD 35,000.
Stony Creek Wind Farm	Removal of blades, hub, nacelle, tower, foundation and grounding/restoration.	Net cost—USD 17,494/turbine.	Approximately USD 10,000/turbine.
Little Raith	Removal of turbines, foundations (1 m), anemometry mast, access roads, control construction, rigid crane supports, soil and seeds to affected areas.	Net cost—GBP 15,000/turbine.	Not informed

Source: Adapted from [57].

Environmental Aspects

The sixth category identified from the systematic review was the environmental aspects. These aspects bring together variables from the environmental aspects that are associated with the decision-making process, the most predominant of which are the following:

(a) Environmental impacts;
(b) Diversification of the electrical matrix (hybridization).

Regarding the category of environmental aspects, it was possible to observe in the studies that it was associated with the assessment of environmental impacts caused throughout the entire life cycle, from the manufacturing of a wind turbine to the disposal process. Furthermore, this aspect was related to the potential for toxicity, the potential for the release of carbon dioxide, climatic conditions, wind conditions and impacts on fauna, flora and the surrounding community.

In a study carried out in Spain, [29] show that the environmental impact must be considered not only for cost–benefit analysis with the country's total energy production in comparison with wind energy, but also to identify improvements in its production process and deactivation. Furthermore, it was identified that the tower has a quantity of steel used in its manufacture, and that despite the environmental impacts generated during its life cycle, this aspect can be mitigated, since 90% of the material is recycled in the dismantling phase.

In another study by Martinez et al. (2010), the decision to decommission was related to the location chosen to install the project, where there were agents that accelerated the wear process of the elements, especially the wind turbines [30]. The authors also highlight that factors related to installation in coastal areas or mountainous areas, which have large temperature fluctuations or gusts of wind, can increase damage to the entire turbine [30].

In this sense, a correlation is also observed between the categories of the environmental aspects and operational aspects in the decision-making process, since in the study carried out in Spain, the authors highlight the advantages in the process of repowering the farm at the end-of-life cycle [38]. These include the possibility of using the foundations of old turbines and replacing them with new, longer turbines, thus reducing the environmental impact caused by civil construction works. Another advantage highlighted is the possibility of reusing existing runways for the new network with new wind turbines, reducing damage to the environment as a result of earthworks and recycling unused materials [38].

The authors identified that, in comparison to Spain's mixed energy production, the reduction in impacts related to global warming was 98.8%, the destruction of the ozone layer was 96.7%, the human toxicity was 89.3% and the terrestrial ecotoxicity was 92.7%. Furthermore, the aging of the farm increases the need for maintenance and, consequently, the environmental impacts, with the recycling of components after dismantling being the determining factor in reducing this impact [29].

In turn, in Ethiopia, Teffera et al. (2020), when analyzing the environmental impact for a service life of 15 and 25 years in three wind farms (AWF 1, AWF 2 and ASWF), with towers of 1.5 MW in the first two and 1.67 MW in the last, they estimated that the best scenario for the farm is the extension of its lifetime by 5 years, so the farm will have a total operating time of 25 years and a rate 80% material recycling. This would mitigate environmental impacts, including toxicity in humans.

Both Teffera et al. (2020) and Kitizing et al. (2020) presented impacts on the ecosystem as a factor considered in feasibility analyses [40,41]. In Germany, according to studies by Bose et al. (2018), experts point out the importance of limiting farm operations in areas of environmental preservation and with a massive presence of birds in order to reduce impacts on biodiversity and the local landscape [85].

In a study carried out in Poland, in which the environmental impacts generated between onshore and offshore wind farms were compared, it was shown that resource depletion was more associated with land-based farms, while the risk to human health was more associated with offshore farms [86]. Furthermore, the negative impacts include the emission of radioactive agents and the potential destruction of the ozone layer, as well as the release of ecotoxic substances, eutrophication processes and others related to land use [86].

In this context, it is important to highlight the existence of legislation that contemplates the prediction of all impacts during the life cycle, as well as regulatory and supervisory bodies that compare, audit and assess the prior planning foreseen during the implementation of a wind farm with the environmental impacts effectively generated, considering the possibilities for eliminating or reducing such identified environmental impacts.

At the end-of-life cycle, the decision to deactivate, through the total or complete decommissioning process, involves the deactivation and dismantling of the wind turbines and the entire infrastructure, with the purpose of re-establishing the area to its original condition. This process can cause environmental impacts, such as the release of greenhouse gases during the transport and disposal of materials, the release of contaminants into the environment and consequences for fauna and flora in the environment.

For environmental improvements to occur, it is important that there are criteria that define goals based on key performance indicators (KPIs), for example, minimizing the carbon footprint or impacts related to toxicity [87]. However, the challenges are not limited only to methodological issues, but also to exogenous factors, such as the creation of policies and legislation that encourage and direct the reuse of materials at the end of their service life [87].

Researchers point out that climate issues are the focus of policies encouraging the use of the carbon footprint as a key performance indicator (KPI). Other means can be used to monitor environmental impacts in order to comply with European legislation on hazardous substances and internal standards on reportable substances. Although both policies deal with toxicity issues, these tools have a different scope than the life cycle assessment (LCA) and are only considered complementary [87].

Wind farm construction licenses typically include a decommissioning requirement, for which developers need to carry out a prior study on the estimated cost of decommissioning the project. These studies consider the type of decommissioning equipment, mobilization costs, what type of material would be discarded and to which landfill it would be transported, what material would be recovered, etc. These requirements differ across the US—for example, developers need to comply with local road-use agreements, but typically do not specify the egress or expected egress for the blades. If an expected outlet for the blades is included, this means that the blades are cut and transported to a landfill [37]. The environmental impacts found are listed, according to the studies, in Table 9.

Table 9. Environmental impacts by decision type.

Generation/Reduction in Environmental Impacts	Cause/Consequence	Decision Type	Studies (SBR Authors)
Waste Treatment/Disposal Policy: ❖ Reduction; ❖ Reuse/reutilization; ❖ Recycling; ❖ Final disposal (incineration, landfills).	Cause	Deactivation/Service Life Extension	[41]; [38]; [37]; [36]; [32]; [29].
Investigation of better materials for the production of wind components.	Cause	Deactivation/Service Life Extension	[41]; [32].
Soil Pollution	Consequence (Final Waste Disposal)	Deactivation/Service Life Extension	[15]; [41].
Groundwater pollution	Consequence (Final Waste Disposal)	Deactivation/Service Life Extension	[15]; [41].
Visual pollution	Consequence (Maintenance or Reduction in the Number of Towers/Wind Generators)	Service Life Extension	[52]; [45]; [15]; [41]; [39].
Noise pollution	Consequence	Service Life Extension	[45]; [15]; [41].

Table 9. *Cont.*

Generation/Reduction in Environmental Impacts	Cause/Consequence	Decision Type	Studies (SBR Authors)
Impacts on fauna, flora and local biodiversity	Consequence	Service Life Extension	[15]; [41]; [40].
Emission of carbon dioxide and greenhouse gases	Consequence	Service Life Extension	[15]; [41]; [13]; [29].
Toxicity in humans	Consequence	Service Life Extension	[40].

Schreiner and Codonho (2018) emphasize that the deactivation of farms is not included in the three-phase environmental licensing and suggest the creation of a fourth licensing phase with the issuance of a deinstallation license for this type of enterprise [88]. In a survey in which ten state bodies responsible for onshore environmental licensing in Brazil participated, the topic of repowering and decommissioning wind farms was considered relevant by all these environmental bodies [89].

The initial construction project of a wind farm must contain planning in case of the decision to deactivate using the concept of the 4Rs of sustainability (reuse, recycle, reduce and rethink) for the treatment of waste and scrap. Reuse, the first and best option, materializes in the resale of wind turbines or parts and components for the secondary market [89].

The second option is recycling, through the sale of waste in the form of scrap (metals like iron, steel, stainless steel, copper, aluminum and lead) which will be recycled and reused. It is important to highlight the importance of this waste being treated appropriately in the recycling process in order to minimize damage caused to the environment.

The third and final option, in cases of impossibility of reusing and recycling, is the final disposal of waste through the incineration or landfilling of the waste generated. In this context, reflection and critical analysis are essential through rethinking, together with research, development and innovation in the sector's industry, the use of materials and the production of parts and components with increasingly greater opportunities for remanufacturing and/or increased recycling potential, considering the reverse logistics process, always aiming to reduce the environmental impacts caused [48].

In the study carried out by Sakellariou (2017), it was identified that end-of-life wind turbines fall into two categories: turbines that are not reusable (scrap value) and those that are reusable. Turbines that can be reused have resale value as used or remanufactured (refurbished) machines, but they represent a smaller subset of the total available turbines. Most of them are stored or landfilled, while the rest are treated for energy recovery in incineration plants [37].

The decision to extend the service life (hybridization with the photovoltaic solar source may exist) through the possibilities of extending the service life (through complete maintenance of the wind turbine and components), retrofit, partial repowering, or total or integral repowering, also contributes to the generation of environmental impacts, such as carbon dioxide emissions generated in the manufacture and transportation of materials, visual pollution (aesthetic impact) and the issue of maintenance and/or noise reduction (noise emission violation) [41].

Therefore, the decision to deactivate or extend the service life of a wind farm must be based on a comprehensive analysis considering legislation (regulatory aspects) and the possible environmental impacts throughout the new life cycle of a wind farm, and its relationship with the future benefits generated through energy production and economic feasibility analysis.

Operational Aspects

The seventh category identified from the systematic review was the operational aspects. These aspects bring together variables from the operational aspects that are associated with the decision-making process, the most predominant of which are the following:

(a) The number of towers, tower height, hub size, rotor diameter, radius Size and minimum distance between towers;
(b) The wind speed, wind direction, capacity factor and potential wind density;
(c) The leasing of the areas (lands) and the expiration of the current contracts (time);
(d) Layout and the wake effect;
(e) Diversification of the electrical matrix (hybridization).

The category of operational aspects was the one that presented the largest number of influencing factors in the decision-making process, registering four in total: layout and the wake effect; the issue of leasing areas (land) regarding the finalization of current contracts; the operational structure of wind towers (number of towers, tower height, hub size, rotor diameter, radius size and minimum distance between towers); and characteristics of the wind potential influencing the amount of energy produced (speed, wind direction, capacity factor and wind density potential).

The evolution of technological development directly affects the capacity and size characteristics of future wind turbines to be produced, such as the number of towers, tower height, hub size, rotor diameter, radius size and minimum distance between towers. Such attributes directly affect both the performance and efficiency of a wind farm [48,90]. The height of the towers influences energy production, as towers located at higher heights take advantage of stronger and more consistent winds, producing more energy [46]. On the other hand, construction and maintenance costs increase.

The larger hub size and larger rotor diameter allow for increased energy production; however, as well as the increased height of the towers, they can increase operational and maintenance costs. After increasing the size of the radius (rotor diameter), there is a need to increase the minimum distance between wind towers, which directly influences the possibilities in relation to leasing areas [50].

Maintaining installed capacity with a smaller number of towers allows the continuity of the leased area with adjustments related to operational aspects, such as the organization and spatial arrangement of wind towers. Another alternative is to increase the number of towers the in search for greater installed capacity and energy production, which influences economic and financial aspects, such as operation and maintenance costs; technical aspects, such as minimum distance; layout; and wake effect [47]. Nonetheless, some challenges are encountered during repowering, due to the presence of existing wind turbines in and around the site, presenting a space constraint [46,49].

In some developed countries like Germany, the United Kingdom and France, there is an incentive through public policies for the development of renewable energy sources, mainly due to the growing need for energy generation. However, these countries face declining rates for new wind farm deployments due to a scarcity of desirable areas, particularly due to legislative restrictions on expanding land use [58,68]. Another strategy to allow the continuation of wind farm operations is repowering, optimizing the use of the area and improving energy production [91].

The advancement of technology contributes positively to increasing efficiency, the use of investment and also profitability [52]. With the reduction in the number of wind turbines, the 55 acres of area are freed up, which can accommodate 14 MW of solar photovoltaic capacity and generate 23,088 MWh of energy annually. Hybrid technology presents greater efficiency and productivity, with 40.9% more passenger load factor (PLF) being able to be generated during repowering, and the site's potential energy yield increases approximately 17 times more compared to the conventional operational capacity. Furthermore, the energy produced is environmentally friendly and does not pollute the environment [46].

In this context, justified by safety reasons, the minimum spacing parameters required between wind turbines are changed, highlighting the need for review, and if necessary, reconfiguration of the layout, which directly affects other operational issues, such as avoiding the wake effect and competitiveness for the best areas and area leasing costs [13,48].

The wake effect is the effect produced between interactions between neighboring wind turbines, as it affects the air flow around them, causing turbulence and reducing wind speed, so that, depending on of the layout of wind towers, a reduced wind speed results in energy production losses [49].

The scenario of finalizing the current leasing contracts for the areas for the projects in operation, and in parallel, the possibility of renewing these contracts in cases of the extension of service life with the possibility of adapting the size of the structure in relation to the space available for installation in the farm and/or the insertion of new wind farms results in greater competitiveness and appreciation for areas with known wind potential [13].

In parallel, and as important as the factors previously presented, the characteristics of the wind potential (speed, wind direction, capacity factor and wind density potential) of the region influence the decision-making process, precisely in the amount of energy produced. This is one of the main factors that directly affects the economic feasibility of extending the project's service life and/or the moment of the decision to extend it due to business strategies, broadly analyzing the market in a comparative way with the projects (prioritization always for the most profitable projects).

5. Conclusions

This article presents innovative points in its development and results obtained. The first point to be highlighted is the application of the PRISMA methodology, not identified in the sample of articles analyzed in this study and in works and research in the area of engineering and the topic addressed, as well as theoretical research following the steps of a systematic literature review (SLR).

The second point is the contribution to the academic area, given the low number of studies focused on the topic of analysis and decisions related to the decision-making process at the end-of-life cycle of onshore wind farms. Based on the methodology used, 26 studies were found that showed factors that influenced the decision-making process of onshore wind farms. Among the countries that stood out were Spain, the United States, the United Kingdom, Germany, China and India.

The third point is the identification of two contexts—the extension of the project's service life or the deactivation and completion of operational activities—systematized into six decision options: total decommissioning (deactivation), total decommissioning with full repowering, partial decommissioning with partial repowering, partial decommissioning with retrofit, partial decommissioning with repowering and hybridization, and partial decommissioning with repowering and retrofit.

Among them, ten indicated partial decommissioning with partial repowering as one of the most feasible options, while seven studies indicated total decommissioning. Furthermore, only five reported experiments carried out, 21 of which dealt with estimates or analyses of future scenarios.

The fourth contribution of the article is presented in the approach to the little explored theme, justified due to the context in which most of the onshore wind farms in operation in the world are not in the final phase of their service life, and a large part of the wind sector and academia is focused for research and innovation in the offshore wind market.

The fifth important point is the importance of the theme being essential for dealing with the decision-making process of wind farms at the end of their service life and with consequences for the planning of the countries' electrical and energy matrices.

The sixth innovation resulting from this review is the identification of the factors that affect the decision at the end-of-life cycle, categorizing them into aspects according to their areas of influence, correlating with other existing aspects.

The most influential types of factors in the decision-making process at the end of the onshore wind farm's life cycle are related to operational aspects, economic aspects, environmental aspects, public policies and technological development. Among the thirteen factors identified, two factors stand out in the decision-making process at the end-of-life cycle: operation and maintenance costs (OPEX) (economic/financial aspect) and the need for analysis regarding the organization and/or a change in layout in order to reduce the impact of the wake effect (operational aspect).

Technological evolution, which is characterized by an increasingly accelerated manner and by its direct correlation with the four operational factors, is a fundamental factor in the decision-making process, enhanced by an increasingly greater business market demand for wind farms. Thus, the aging of a farm is an important factor; however, it is not an exclusive condition in the decision-making process, since studies were identified highlighting other aspects as essential for possible feasibility.

Given the increase in farms reaching this end-of-life context, the scarcity of studies on this topic highlights the need to carry out research reporting other experiences (empirical studies) in order to propose greater development in the learning curve to the processes of deactivation and extension of service life. In this scenario, the importance of identifying the factors, types of factors and variables inserted in the economic/financial pillar influencing the decision-making process at the end of the service life of onshore wind farms is emphasized, as well as better support decisions regarding the future of these farms.

Finally, the need to carry out and/or update periodic planning for the growth of the electrical matrix stands out, including decisions to deactivate and extend the operational life of onshore wind farms, avoiding under-sizing the electrical energy transmission infrastructure.

Author Contributions: Conceptualization, J.A.N. and K.M.A.; methodology, J.A.N. and R.L.P.d.C.; validation, J.A.N., R.L.P.d.C., D.C.d.M., K.M.A., A.M.S., R.M.d.V., L.H.d.S., E.L.d.S.C. and M.O.A.G.; formal analysis, J.A.N. and R.L.P.d.C.; research, J.A.N., R.L.P.d.C., D.C.d.M., A.M.S., R.M.d.V., L.H.d.S. and E.L.d.S.C.; resources, J.A.N.; data curation, J.A.N.; writing—preparation of the original draft, J.A.N. and D.C.d.M. and K.M.A.; writing—review and editing, J.A.N. and K.M.A.; visualization, J.A.N. and M.O.A.G.; supervision, J.A.N. and M.O.A.G.; project administration, J.A.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data used in the article can be found in the references and in the articles in the Appendix A.

Acknowledgments: Our acknowledgment to: Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES).

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Characterization of the factors and variables that influenced decision making at the end of the onshore wind farm life cycle and possible variables.

n	Authors	Title	Year	Country	Decision	Categories	Factors	Variables
1	[29]	Life-cycle assessment of a 2-MW rated power wind turbine: CML method	2009	Spain	Total Decommissioning (shutdown)	Environmental Aspects	1. High environmental impacts in relation to the economic viability of the park, because the production does not offset the environmental impacts generated.	❖ Costs with studies and technical and environmental feasibility analyses; ❖ Quantity of energy produced; ❖ Revenues from the sale of electric energy (operating revenues).
						Economic/Financial Aspects		
						Economic/Financial Aspects	2. Economic infeasibility due to lower than expected annual energy production.	
2	[30]	LCA sensitivity analysis of a multi-megawatt wind turbine	2010	Spain	Total Decommissioning (shutdown)	Environmental Aspects	1. Place not appropriate (presence of degrading agents—accelerated depreciation) and higher maintenance costs (OPEX).	❖ Components' and parts' depreciation rate; ❖ Costs with maintenance of parts and components (preventive, predictive and corrective); ❖ Quantity of energy produced; ❖ Revenues from the sale of electric energy (operating revenues).
						Operational Aspects		
						Environmental Aspects	2. Presence of agents that accelerate the degradation of the blades.	
						Operational Aspects		
3	[31]	An Exit and Entry Study of Renewable Power Producers: A Real Options Approach	2012	USA	Total Decommissioning (shutdown)	Economic/Financial Aspects	1. Operation and maintenance costs in relation to operating output (OPEX).	❖ Parts' and components' maintenance costs (preventive, predictive and corrective).
						Technological Development in the Sector		
						Operational Aspects		
						National Energy Directive (National Aspects)	2. Subsidies and political incentives for non-interruption of operation or premature exit; 3. Political and economic incentives for insertion in new ventures and production of more energy.	❖ Public policies and government incentives (federal and state) and tax benefits; ❖ Reduction or exemption of costs with licenses and permits; ❖ Reduction or exemption of expenses with taxes and/or duties; ❖ Revenues from the sale of electric energy (operating revenues).
						Public Policies and Regulatory Aspects		
						Economic/Financial Aspects		
4	[32]	Producer responsibility: Defining the incentive for recycling composite wind turbine blades in Europe	2012	United Kingdom	Total Decommissioning (shutdown)	Economic/Financial Aspects	1. Material residual value, recycling costs and disposal costs.	❖ Costs with transport of the waste(s); ❖ Costs with removal of cables (internal and external) and connections; ❖ Disposal costs (landfill, incineration, recycling, remanufacturing or reuse) of blades, metals, concrete, organic material, electronic components; ❖ Sales revenue (wind turbines for reuse—second-hand market); ❖ Sales revenue (waste and scrap—metals such as iron, steel, stainless steel, copper, aluminum and lead).
						Environmental Aspects		
						National Energy Directive (National Aspects)	2. Waste disposal tax.	❖ Public policies and governmental incentives (federal and state) and tax benefits; ❖ Reduction or exemption of costs with waste disposal (landfills, incineration, recycling, remanufacturing or reuse); ❖ Reduction or exemption of expenses with taxes and/or duties.
						Public Policies and Regulatory Aspects		
						Economic/Financial Aspects		
						Economic/Financial Aspects	3. Disposal and disassembly costs including labor, equipment, transportation and any external costs.	❖ Crane transportation costs; ❖ Cost of setting up the crane(s); ❖ Cost of dismantling/removal of the wind turbine; ❖ Cost of cutting the blades; ❖ Cost of separation (cutting) of the tower and nacelle; ❖ Foundation demolition costs; ❖ Foundation material cutting costs; ❖ Cable excavation—(removal cost); ❖ Substation and transformer removal costs;
						Logistics and Infrastructure Aspects		
						Operational Aspects		

Table A1. *Cont.*

n	Authors	Title	Year	Country	Decision	Categories	Factors	Variables
						Economic/Financial Aspects Operational Aspects Environmental Aspects	4. Cost to remove and/or reuse.	❖ Removal costs for cables (internal and external) and connections; ❖ Waste transportation costs; ❖ Costs with disposal (landfill, incineration, recycling, remanufacturing or reuse) of veneers, metals, concrete, organic material, electronic components; ❖ Costs with studies and technical and environmental feasibility analyses; ❖ Quantity of energy produced; ❖ Revenues from the sale of electric energy (operating revenues).
						Public Policies and Regulatory Aspects Environmental Aspects	5. End of life legislation; 6. Environmental impacts.	
5	[33]	A multi-period modelling and optimization approach to the planning of China's power sector with consideration of carbon dioxide mitigation	2012	China	Partial Decommissioning with Retrofit	National Energy Directive (National Aspects) Logistics and Infrastructure Aspects Operational Aspects Economic/Financial Aspects	1. Optimize the costs of the country's electrical sector.	❖ General costs with generation, transmission and distribution of energy.
						Environmental Aspects Operational Aspects Economic/Financial Aspects	2. Mitigate carbon dioxide emissions; 3. Impacts on carbon prices and credits.	❖ Costs with carbon credit purchase (carbon emission above that established).
						Operational Aspects	4. Annual operating time; 5. Expected useful life.	❖ Capacity factor (energy production time); ❖ The time of study and analysis of technical and economic feasibility.
						Economic/Financial Aspects Public Policies and Regulatory Aspects	6. Higher capital cost compared to building nuclear power plants.	❖ Cost of equity (required return on invested equity)—CAPM; ❖ Country risk premium; ❖ Third-party capital cost (interest rate); ❖ Weighted average cost of capital—W.A.C.C; ❖ Minimum rate of attractiveness/minimum acceptable rate (discount rate).
						Economic/Financial Aspects Technological Development in the Sector Operational Aspects	7. Operation and maintenance cost (OPEX).	❖ Components' and parts' depreciation rate; ❖ Costs with maintenance of parts and components (preventive, predictive and corrective); ❖ Quantity of energy produced; ❖ Revenues from the sale of electric energy (operating revenues).
						National Energy Directive (National Aspects) Public Policies and Regulatory Aspects Technological Development in the Sector	8. Incentive to the energy transition as a result of the search for a reduction in fossil fuel use and pollutant emissions.	❖ Public policies and governmental incentives (federal and state) and tax benefits; ❖ Investments in research, development and innovation in the national energy sector; ❖ Reduction or exemption of costs with licenses and permits; ❖ Reduction or exemption of expenses with taxes and/or duties; ❖ Reduction or exemption of costs with waste disposal (landfills, incineration, recycling, remanufacturing or reuse); ❖ Revenues from the sale of electric energy (operating revenues).

Table A1. *Cont.*

n	Authors	Title	Year	Country	Decision	Categories	Factors	Variables
6	[13]	Preparing for end of service life of wind turbines	2013	USA	Total Decommissioning with full Repowering	Operational Aspects Logistics and Infrastructure Aspects Economic/Financial Aspects	1. Expiration of contracts and land leases for wind farms.	❖ Costs with the negotiation of contracts (CAPEX) for the leasing of properties (areas/land); ❖ Operating costs (OPEX) with the leasing of properties (areas/land).
						National Energy Directive (National Aspects) Public Policies and Regulatory Aspects Economic/Financial Aspects	2. Attractive financial incentives for continued operation.	❖ Public policies and government incentives (federal and state) and tax benefits; ❖ Reduction or exemption of costs with licenses and permits; ❖ Reduction or exemption of expenses with taxes and/or duties; ❖ Reduction or exemption from costs with waste disposal (landfills, incineration, recycling, remanufacturing or reuse); ❖ Revenues from the sale of electricity (operating revenues).
						Technological Development in the Sector Logistics and Infrastructure Aspects Operational Aspects Economic/Financial Aspects	3. Possibility of increased power per area and technological advancement; 4. Reducing the number of units and the cost of operation and maintenance (OPEX).	❖ Costs with technical, economic and environmental feasibility studies; ❖ Possible costs for inspections and certifications; ❖ Possible costs with acquisition of new components for wind farms; ❖ Costs with maintenance of parts and components (preventive, predictive and corrective); ❖ Quantity of energy produced; ❖ Revenues from sale of electricity (operating revenues).
						Logistics and Infrastructure Aspects Operational Aspects	5. Opportunities derived from existing logistics and infrastructure aspects, network connections and historical operation.	❖ Logistics and infrastructure aspects and logistics adaptation costs; ❖ Costs with rebuilding or construction of new substations and grid connection; ❖ Costs with rebuilding of foundations or construction of new foundations.
						Operational Aspects Environmental Aspects Logistics and Infrastructure Aspects	6. Opportunity for remanufacturing and good conditions for reverse logistics.	❖ Reverse logistics costs; ❖ Costs with component remanufacturing (towers, blades, rotors, nacelles, generator, main box, gear shaft and electrical components).
						Economic/Financial Aspects Public Policies and Regulatory Aspects Environmental Aspects Operational Aspects	7. Cost of decommissioning assessed during decision planning; 8. Material residual value, recycling costs and disposal costs.	❖ Costs with transport of the waste(s); ❖ Costs with removal of cables (internal and external) and connections; ❖ Costs with disposal (landfill, incineration, recycling, remanufacturing or reuse) of the blades, metals, concrete, organic material, electronic components; ❖ Costs of removing cables (internal and external) and connections; ❖ Disposal costs (landfill, incineration, recycling, remanufacturing or reuse) of blades, metals, concrete, organic material, electronic components; ❖ Costs with remanufacturing of components (towers, blades, rotors, nacelles, generator, main box, gear shaft and electrical components); ❖ Sales revenue (wind turbine parts for reuse—second-hand market); ❖ Sales revenue (waste and scrap—metals such as iron, steel, stainless steel, copper, aluminum and lead).
7	[34]	Comparative life cycle assessment of tubular wind towers and foundations—Part 2: Life cycle analysis	2014	Portugal	Partial Decommissioning with partial Repowering and retrofit	Environmental Aspects Economic/Financial Aspects	1. Recycling rate; 2. Material reuse rate; 3. Final destination of waste.	
						Environmental Aspects Logistics and Infrastructure Aspects	4. Structure that enables remanufacturing and generates less environmental impact.	
						Technological Development in the Sector Operational Aspects Economic/Financial Aspects Logistics and Infrastructure Aspects	5. The height of the towers that support the increase in scale, of power with technological upgrade.	❖ Amount of energy produced; ❖ Revenues from the sale of electric energy (operating revenues).

Table A1. *Cont.*

n	Authors	Title	Year	Country	Decision	Categories	Factors	Variables
8	[35]	Repowering a Windfarm—A Techno-Economic Approach	2015	India	Partial Decommissioning with partial Repowering	Economic/Financial Aspects	1. Levelized annual energy generation cost (ALCoG).	❖ Levelized cost of energy (LCOE).
						Operational Aspects	2. Payback period and internal rate of return (IRR);	❖ Internal rate of return (IRR); ❖ Payback;
							3. Layout review and reconfiguration to avoid the wake effect.	❖ Amount of energy produced; ❖ Revenues from the sale of electric energy (operating revenues).
9	[36]	Wind turbine blade waste in 2050	2017	England	Partial Decommissioning with partial Repowering	Operational Aspects Economic/Financial Aspects	1. Seven or 18 years of blades in operation; 2. Fatigue in hull connections and root connections related to repair (wear of the structure).	❖ Costs with maintenance of parts and components (preventive, predictive and corrective); ❖ Quantity of energy produced; ❖ Revenues from the sale of electricity (operating revenues); ❖ Waste transportation costs; ❖ Costs with disposal (landfill, incineration, recycling, remanufacturing or reuse) of blades, metals, concrete, organic material, electronic components; ❖ Sales revenue (wind turbine parts for reuse—second-hand market); ❖ Sales revenue (waste and scrap—metals such as iron, steel, stainless steel, copper, aluminum and lead).
						Technological Development in the Sector Operational Aspects Logistics and Infrastructure Aspects	3. Scale and power increase with technological upgrade.	❖ Quantity of energy produced; ❖ Revenues from the sale of electricity (operating revenues).
10	[37]	Current and potential decommissioning scenarios for end-of-life composite wind blades	2017	USA	Total Decommissioning (shutdown)	Public Policies and Regulatory Aspects Operational Aspects Environmental Aspects	1. Validity of licenses for park operation.	❖ Costs with licenses and permits.
						Economic/Financial Aspects Operational Aspects Environmental Aspects Public Policies and Regulatory Aspects	2. Cost of life extension in relation to interruption of operation and/or recycling.	❖ Costs with transportation of the waste(s); ❖ Disposal costs (landfills, incineration, recycling, remanufacturing or reuse) of veneers, metals, concrete, organic material, electronic components.
11	[38]	Life cycle assessment of a wind farm repowering process	2018	Spain	Partial Decommissioning with partial Repowering	Technological Development in the Sector Operational Aspects Logistics and Infrastructure Aspects Economic/Financial Aspects	1. Scale and power increase with technological upgrade; 2. Layout review and reconfiguration to avoid the wake effect.	❖ Quantity of energy produced; ❖ Revenues from the sale of electricity (operating revenues).

Table A1. *Cont.*

n	Authors	Title	Year	Country	Decision	Categories	Factors	Variables
12	[39]	Analysis of the Repowering Wind Farm of Sidi-Daoud in Tunisia	2019	Tunisia	Total Decommissioning with full Repowering	Technological Development in the Sector Operational Aspects Economic/Financial Aspects	1. Presence of fixed-speed turbines that have lower power ratings than variable-speed turbines; 2. Operation and maintenance cost reduction (OPEX); 3. Number of wind turbines reduced to review and reconfigure layout to avoid wake effect.	❖ Quantity of energy produced; ❖ Revenues from the sale of electricity (operating revenues).
						Technological Development in the Sector Operational Aspects Logistics and Infrastructure Aspects	4. Scale and power increase with technological upgrade.	
						Operational Aspects	5. Generate grid stability in case of voltage drop, because of the converters that act as static compensators during the fault.	
						Environmental Aspects Operational Aspects	6. Presence of noise.	❖ Costs with parts and components maintenance (preventive, predictive and corrective); ❖ Quantity of energy produced; ❖ Revenues from the sale of electricity (operating revenues).
13	[40]	Life cycle assessment of wind farms in Ethiopia	2020	Ethiopia	Partial Decommissioning with Retrofit	Environmental Aspects	1. Mitigation of environmental impacts and toxicity in humans.	❖ Costs with studies and analysis of environmental impacts and technical and environmental viability.
						Environmental Aspects Operational Aspects Economic/Financial Aspects	2. Increasing the recycling potential of the park elements.	❖ Costs with transportation of the waste(s); ❖ Costs with disposal (landfill, incineration, recycling, remanufacturing or reuse) of veneers, metals, concrete, organic material, electronic components; ❖ Sales revenue (wind turbine parts for reuse—second-hand market); ❖ Sales revenue (waste and scrap—metals such as iron, steel, stainless steel, copper, aluminum and lead).
14	[15]	Environmental impacts of decommissioning: Onshore versus offshore wind farms	2020	England and Scotland	Total Decommissioning (shutdown)	Environmental Aspects Public Policies and Regulatory Aspects	1. Environmental impacts; 2. Legislation that provides for the analysis of environmental impacts during the entire life cycle.	❖ Costs with studies and analysis of environmental impacts and technical and environmental viability.
						Operational Aspects Economic/Financial Aspects Public Policies and Regulatory Aspects Environmental Aspects	3. Presentation of defined decommissioning program.	❖ Costs with studies and analysis of environmental impacts and technical and environmental feasibility; ❖ Cost of dismantling/removal of the wind turbine; ❖ Cost of cutting the blades; ❖ Cost of separation (cutting) of the tower and nacelle; ❖ Foundation demolition costs; ❖ Foundation material cutting cost(s); ❖ Cable-digging cost (removal cost); ❖ Substation and transformer removal costs; ❖ Costs of removing cables (internal and external) and connections; ❖ Waste transportation costs; ❖ Costs with disposal (landfill, incineration, recycling, remanufacture or reuse) of blades, metals, concrete, organic material, electronic components; ❖ Costs with remanufacturing of components (towers, blades, rotors, nacelles, generator, main box, gear shaft and electrical components); ❖ Sales revenue (wind turbine parts for reuse—second-hand market); ❖ Sales revenue (waste and scrap—metals such as iron, steel, stainless steel, copper, aluminum and lead).

Table A1. *Cont.*

n	Authors	Title	Year	Country	Decision	Categories	Factors	Variables
						Public Policies and Regulatory Aspects Environmental Aspects Operational Aspects Logistics and Infrastructure Aspects Economic/Financial Aspects	4. Time of lease and land-use authorization.	❖ Operating costs (OPEX) with the leasing of properties (areas/land).
						Economic/Financial Aspects Operational Aspects Technological Development in the Sector	5. Simulation of the various life extension or decommissioning scenarios for later decision making.	❖ Costs with studies and technical, environmental and economic feasibility analyses.
15	[45]	Analysis of scenarios for repowering wind farms in Brazil	2021	Brazil	Partial Decommissioning with partial Repowering	Economic/Financial Aspects	1. Economic evaluation relating internal rate of return (IRR), payback time (PB), selling rate and operating and maintenance cost (OPEX).	❖ Internal rate of return (IRR); ❖ Discounted payback (PBD); ❖ Parts and components maintenance costs (preventive, predictive and corrective); ❖ Revenues from the sale of electricity (operating revenues).
						Operational Aspects Economic/Financial Aspects	2. Layout review and reconfiguration to avoid the wake effect.	❖ Quantity of energy produced; ❖ Revenues from the sale of electricity (operating revenues).
						National Energy Directive (National Aspects) Public Policies and Regulatory Aspects Economic/Financial Aspects	3. Changes in incentives for alternative sources with discounts of 50% or more in the transmission system use tariff and distribution system use tariff from 30 MW to 300 MW.	❖ Public policies and government incentives (federal and state) and tax benefits; ❖ Reduction in costs with transmission and distribution tariffs.
						Economic/Financial Aspects Operational Aspects Technological Development in the Sector	4. Simulation of the various life extension or decommissioning scenarios for subsequent decision making.	❖ Costs with studies and technical, environmental and economic feasibility analyses.
16	[41]	Multifaceted drivers for onshore wind energy repowering and their implications for energy transition	2020	Denmark	Total Decommissioning with full Repowering	Operational Aspects Economic/Financial Aspects Technological Development in the Sector	1. Infeasibility of older wind turbines to operate longer; 2. Energy production below expectations; 3. Failure rate and downtime; 4. Layout review and reconfiguration to avoid the wake effect; 5. Radius of 1.5 times the total height of the new wind turbine and minimum distance to avoid the danger of a turbine tower collapse.	❖ Costs with parts' and components' maintenance (preventive, predictive and corrective); ❖ Capacity factor (energy production time); ❖ Quantity of energy produced; ❖ Revenues from the sale of electricity (operating revenues).
						Environmental Aspects	6. Noise emission violation; 7. Visual pollution (aesthetic impact).	❖ Costs with fines and penalties; ❖ Compliance costs; ❖ Costs with standards adaptation; ❖ Costs with studies and analysis of environmental impacts and technical and environmental feasibility; ❖ Parts and components maintenance costs (preventive, predictive and corrective).
						Logistics and Infrastructure Aspects Operational Aspects	8. Physical need for the installation of new turbines, new foundations, access roads and grid infrastructure.	❖ Costs with reconstruction of foundations or construction of new foundations; ❖ Costs for reconstruction or construction of new substations and grid connection; ❖ New interconnection cable costs; ❖ Costs for layout revision and reconfiguration (belt effect); ❖ Planning, project development, engineering and civil works costs; ❖ Infrastructure and logistics adaptation costs.

Table A1. *Cont.*

n	Authors	Title	Year	Country	Decision	Categories	Factors	Variables
						Public Policies and Regulatory Aspects	9. Political factors that influence dismantling or repowering.	❖ Public policies and government incentives (federal and state) and tax benefits; ❖ Reduction or exemption of costs with licenses and permits; ❖ Reduction or exemption of expenses with taxes and/or duties; ❖ Reduction or exemption of costs with waste disposal (landfills, incineration, recycling, remanufacturing or reuse).
17	[42]	20% of US electricity from wind will have limited impacts on system efficiency and regional climate	2020	USA	Partial Decommissioning with partial Repowering	Environmental Aspects	1. Interannual variability of wind resources, mainly due to climatic phenomena such as El Niño and La Niña.	❖ Operating costs (OPEX) with the leasing of properties (areas/land); ❖ Quantity of energy produced; ❖ Revenues from the sale of electricity (operating revenues).
						Operational Aspects	2. Wind speed.	
						Operational Aspects Economic/Financial Aspects	3. Losses in energy production due to the wake effect; 4. Organization of the layout to avoid competition from the land.	
						Technological Development in the Sector Operational Aspects Economic/Financial Aspects	5. Smaller capacity and WT dimension are replaced by larger models.	❖ Capacity factor (energy production time); ❖ Quantity of energy produced; ❖ Revenues from the sale of electricity (operating revenues).
18	[43]	Partial repowering analysis of a wind farm by turbine hub height variation to mitigate neighboring wind farm wake interference using mesoscale simulations	2020	Pakistan	Partial Decommissioning with partial Repowering	Operational Aspects Economic/Financial Aspects	1. Review and reconfiguration of the internal and external layout (in relation to neighboring farms) to avoid the wake effect; 2. Energy deficit due to interference from the neighboring wind farm.	❖ Quantity of energy produced; ❖ Revenues from the sale of electricity (operating revenues).
						Operational Aspects	3. Deficit wind speed and need for change in layout and height of towers.	❖ Quantity of energy produced; ❖ Revenues from the sale of electricity (operating revenues).
						Economic/Financial Aspects	4. Turbine hub height to avoid wind overlap.	
19	[44]	Optimization of the wind farm layout by repowering the old wind farm and integrating solar power plants: A case study	2020	India	Partial Decommissioning with Repowering and Hybridization	Operational Aspects Environmental Aspects	1. Strong solar irradiation from March to September.	❖ Quantity of energy produced; ❖ Revenues from the sale of electricity (operating revenues).
						Operational Aspects Economic/Financial Aspects	2. Wind density potential at higher heights.	
						Operational Aspects Economic/Financial Aspects	3. Layout review and reconfiguration to avoid the wake effect.	
						Logistics and Infrastructure Aspects Operational Aspects	4. Ensure the safety of neighboring construction and optimize the use of the existing network and logistics and infrastructure aspects.	❖ Logistics and infrastructure aspects and logistics adaptation costs; ❖ Specialized labor costs.
						Operational Aspects Economic/Financial Aspects	5. Need for increased capabilities and performance.	❖ Investments (CAPEX) in the acquisition and installation of the photovoltaic plates; ❖ Operation and maintenance costs (OPEX) of the photovoltaic panels; ❖ Capacity factor (energy production time); ❖ Quantity of energy produced; ❖ Revenues from the sale of electricity (operating revenues).
						Operational Aspects	6. Hybridization due to the availability of shade-free areas; 7. Larger turbines release shadow regions.	

Table A1. *Cont.*

n	Authors	Title	Year	Country	Decision	Categories	Factors	Variables
						Operational Aspects Technological Development in the Sector Economic/Financial Aspects	8. Obsolete parts, resulting in a substantial increase in operation and maintenance costs (OPEX) and a decrease in total generation.	❖ Costs with parts and components maintenance (preventive, predictive and corrective); ❖ Quantity of energy produced; ❖ Revenues from the sale of electricity (operating revenues).
20	[46]	Leveraging on repowering of wind sites for potential wind-solar hybrid capacities: A case study	2021	India	Partial Decommissioning with Repowering and Hybridization	Operational Aspects	1. Area free of shade and obstacles is exploited for the installation of solar photovoltaic capacity; 2. High level of insolation.	❖ Quantity of energy produced; ❖ Revenues from the sale of electricity (operating revenues).
						Technological Development in the Sector Operational Aspects Economic/Financial Aspects	3. Increasing wind turbine hub and rotor diameter.	
						Operational Aspects Economic/Financial Aspects	4. Arrangement of wind turbines to take advantage of maximum speeds; 5. Layout review and reconfiguration to avoid the wake effect.	
						Operational Aspects	6. Reduction in occupancy by new, more efficient wind turbines so that free areas can be taken advantage of by photovoltaic panels.	
						Economic/Financial Aspects Technological Development in the Sector Operational Aspects	7. Reduced maintenance and operating costs (OPEX).	❖ Costs with parts and components maintenance (preventive, predictive and corrective); ❖ Quantity of energy produced; ❖ Revenues from the sale of electricity (operating revenues).
						Environmental Aspects Operational Aspects	8. Noise reduction.	❖ Costs with standards adaptation; ❖ Costs with studies and analysis of environmental impacts and technical and environmental feasibility; ❖ Parts and components maintenance costs (preventive, predictive and corrective).
						Logistics and Infrastructure Aspects Operational Aspects	9. Improved integration with the network.	❖ Costs with adaptation and/or reconstruction or construction of new substations and grid connection (logistics and infrastructure aspects).
						Technological Development in the Sector Operational Aspects Logistics and Infrastructure Aspects Economic/Financial Aspects	10. Reactive power—new machines consume less reactive power; 11. Faster technological development.	❖ Operating costs (OPEX) with the leasing of properties (areas/land); ❖ Quantity of energy produced; ❖ Revenues from the sale of electricity (operating revenues).
						Operational Aspects Economic/Financial Aspects	12. Increased wind generation without the need for additional land.	
21	[47]	Optimization of a wind farm by coupled actuator disk and mesoscale models to mitigate neighboring wind farm wake interference from repowering perspective	2021	Pakistan	Partial Decommissioning with partial Repowering	Operational Aspects Economic/Financial Aspects	1. The energy deficit in nine out of thirty-three machines due to the treadmill effect between farms.	❖ Capacity factor (energy production time); ❖ Quantity of energy produced; ❖ Revenues from the sale of electricity (operating revenues).
						Operational Aspects	2. Prevailing wind direction; 3. Irregular tower spacing.	
						Environmental Aspects Economic/Financial Aspects	4. Adjustments due to variations in temperatures throughout the day that influence wind speed.	

Table A1. *Cont.*

n	Authors	Title	Year	Country	Decision	Categories	Factors	Variables
22	[48]	Regional rotor blade waste quantification in Germany until 2040	2021	Germany	Total Decommissioning (shutdown)	Operational Aspects Public Policies and Regulatory Aspects Economic/Financial Aspects	1. Aging structure with stipulated time limit (≤20 years) for receiving financial incentives.	❖ Public policies and governmental incentives (federal and state) and tax benefits; ❖ Reduction or exemption of costs with waste disposal (recycling).
						Public Policies and Regulatory Aspects Economic/Financial Aspects	2. End of the term for incentives by the country's renewable energy sources law.	
						Operational Aspects Economic/Financial Aspects	3. Wind load zones, wind turbulence and underutilized wind turbine sites.	❖ Capacity factor (energy production time); ❖ Quantity of energy produced; ❖ Revenues from the sale of electricity (operating revenues).
						Environmental Aspects	4. Environmental impacts that outweigh the benefits generated through energy generation.	❖ Costs with studies and technical and environmental viability analyses; ❖ Quantity of energy produced; ❖ Revenues from the sale of electricity (operating revenues).
23	[49]	Sounding out the repowering potential of wind energy—A scenario-based assessment from Germany	2021	Germany	Total Decommissioning with full Repowering	Operational Aspects	1. Geographical constraints associated with loss of potential area.	❖ Quantity of energy produced; ❖ Revenues from the sale of electricity (operating revenues).
						Operational Aspects Economic/Financial Aspects	2. Minimum spacing required between wind turbines to avoid wake effect.	❖ Capacity factor (energy production time); ❖ Quantity of energy produced; ❖ Revenues from the sale of electricity (operating revenues).
						Logistics and Infrastructure Aspects Technological Development in the Sector Operational Aspects Economic/Financial Aspects	3. Increased energy needs with replacement of larger structures; 4. Appropriateness of the size of the structure in relation to the space available for installation in the park.	
						Operational Aspects Economic/Financial Aspects	5. Aging structure with stipulated time limit (≤20 years) for receiving financial incentives.	❖ Public policies and government incentives (federal and state) and tax benefits; ❖ Reduction or exemption of costs with licenses and permits; ❖ Reduction or exemption of expenses with taxes and/or duties; ❖ Reduction or exemption of costs with waste disposal (landfill, incineration, recycling, remanufacturing or reuse); ❖ Revenues from the sale of electricity (operating revenues).
24	[50]	Energy savings analysis in logistics of a wind farm repowering process: A case study	2021	France	Partial Decommissioning with partial Repowering	Economic/Financial Aspects	1. Lower cost than full repowering.	❖ Costs with studies and technical, environmental and economic feasibility analyses.
						Operational Aspects Economic/Financial Aspects	2. Life extension for another 15 years.	❖ The time for study and analysis of technical and economic feasibility.
						Operational Aspects Economic/Financial Aspects	3. Need for increased energy generation.	❖ Capacity factor (energy production time); ❖ Quantity of energy produced; ❖ Revenues from the sale of electricity (operating revenues).
						Technological Development in the Sector Operational Aspects Logistics and Infrastructure Aspects Economic/Financial Aspects	4. Replacement with towers of greater power and efficiency.	

Table A1. *Cont.*

n	Authors	Title	Year	Country	Decision	Categories	Factors	Variables
						Public Policies and Regulatory Aspects; Environmental Aspects; Economic/Financial Aspects; Technological Development in the Sector	5. Legal, financial, environmental, human resources, technological and organizational factors.	❖ Costs with studies and technical, environmental and economic feasibility analyses.
						Logistics and Infrastructure Aspects; Economic/Financial Aspects	6. Logistics of the repowering process.	❖ Logistics and infrastructure aspects and logistics adaptation costs.
25	[51]	Economic and sensitivity analysis on wind farm end-of-life strategies	2022	Brazil	Partial Decommissioning with partial Repowering	Operational Aspects; Economic/Financial Aspects	1. Capacity factor.	❖ Capacity factor (energy production time); ❖ Quantity of energy produced; ❖ Revenues from the sale of electricity (operating revenues).
						Economic/Financial Aspects	2. Investments (CAPEX).	❖ Investments (CAPEX) in the acquisition and installation of wind farm components.
						Economic/Financial Aspects; Operational Aspects	3. Decommissioning costs, energy tariff, OPEX and RECs that could affect the NPV and IRR of the cash flow.	❖ Costs with studies and analysis of environmental impacts and technical and environmental viability; ❖ Parts' and component's maintenance costs (preventive, predictive and corrective); ❖ Price of electric energy sale; ❖ Quantity of energy produced; ❖ Revenues from the sale of electricity (operating revenues); ❖ Wind turbine dismantling/removal cost; ❖ Blade-cutting cost; ❖ Tower and nacelle separation (cutting) costs; ❖ Foundation demolition cost(s); ❖ Foundation material cutting costs; ❖ Costs with cable excavation—(cost with removal); ❖ Substation and transformer removal costs; ❖ Costs for removal of cables (internal and external) and connections; ❖ Waste transportation costs; ❖ Disposal costs (landfill, incineration, recycling, remanufacturing or reuse) of blades, metals, concrete, organic material, electronic components); ❖ Costs with remanufacturing of components (towers, blades, rotors, nacelles, generator, main box, gear shaft and electrical components); ❖ Sales revenue (wind turbine parts for reuse—second-hand market); ❖ Sales revenue (waste and scrap—metals such as iron, steel, stainless steel, copper, aluminum and lead).
						Operational Aspects; Economic/Financial Aspects	4. Impossibility of reconditioning parts.	
26	[52]	Multi-dimensional barrier identification for wind farm repowering in Spain through an expert judgment approach	2022	Spain	Partial Decommissioning with partial Repowering	Technological Development in the Sector; Operational Aspects; Economic/Financial Aspects	1. Installation of taller machines with larger rotor diameters.	Capacity factor (energy production time);Quantity of energy produced;Revenues from the sale of electricity (operating revenues).
						Operational Aspects; Environmental Aspects; Economic/Financial Aspects	2. Very strong winds or very extreme weather conditions where it would be less risky to maintain small wind turbine generators.	

Table A1. *Cont.*

n	Authors	Title	Year	Country	Decision	Categories	Factors	Variables
						Operational Aspects Economic/Financial Aspects	3. Ripple effect generated between wind turbines in the farm and between other farms.	❖ Quantity of energy produced; ❖ Revenues from the sale of electricity (operating revenues).
						Logistics and Infrastructure Aspects Operational Aspects	4. Inability of the electrical grid to evacuate the generated power.	❖ Logistics and infrastructure aspects and logistics adaptation costs; ❖ Costs with rebuilding or construction of new substations and grid connection.
						Economic/Financial Aspects Technological Development in the Sector Operational Aspects	5. Operation and maintenance costs (OPEX).	❖ Costs with parts and components maintenance (preventive, predictive and corrective); ❖ Quantity of energy produced; ❖ Revenues from the sale of electricity (operating revenues).
						Economic/Financial Aspects	6. The price of the new wind generator is a determining factor in assessing the profitability of repowering.	❖ Investments (CAPEX) in the acquisition and installation of wind farm components.
						Public Policies and Regulatory Aspects Economic/Financial Aspects	7. Indirect economic incentives can be attractive to investors.	❖ Public policies and government incentives (federal and state) and tax benefits; ❖ Reduction or exemption of costs with licenses and permits; ❖ Reduction or exemption of expenses with taxes and/or duties; ❖ Reduction or exemption of costs with waste disposal (landfills, Incineration, recycling, remanufacturing or reuse); ❖ Reduction or exemption of costs with licenses and permits; ❖ Reduction or exemption of expenses with taxes and/or duties; ❖ Reduction or exemption of costs with waste disposal (landfills, incineration, recycling, remanufacturing or reuse); ❖ Revenues from the sale of electricity (operating revenues).
						Economic/Financial Aspects	8. Guarantees to protect investments against a reduction in the average value of market clearing prices and an increase in their volatility.	❖ Public policies and governmental incentives (federal and state) and tax benefits; ❖ Electricity selling price; ❖ Revenues from the sale of electricity (operating revenues).

References

1. Chen, T.-Y.; Yeh, T.-L.; Hsuan, Y. Comparative Analysis of Endowments Effect Renewable Energy Efficiency Among OECD Countries. In *New Developments in Renewable Energy*; IntechOpen: London, UK, 2013; pp. 193–211.
2. Sampaio, P.G.V.; Aguirre González, M.O.; Monteiro de Vasconcelos, R.; dos Santos, M.A.T.; Jácome Vidal, P.d.C.; Pereira, J.P.P.; Santi, E. Prospecting technologies for photovoltaic solar energy: Overview of its technical-commercial viability. *Int. J. Energy Res.* **2020**, *44*, 651–668. [CrossRef]
3. International Renewable Energy Agency. *Tripling Renewable Power and Doubling Energy Efficiency by 2030: Crucial Steps towards 1.5°*, 2023th ed.; IRENA: Abu Dhabi, United Arab Emirates, 2023; 62p. Available online: www.irena.org/publications (accessed on 14 April 2023).
4. Global Wind Energy Council. Global Wind Report 2022. GWEC. 2022. Available online: https://gwec.net/global-wind-report-2022/ (accessed on 7 January 2023).
5. Cooperman, A.; Eberle, A.; Lantz, E. Wind turbine blade material in the United States: Quantities, costs, and end-of-life options. *Resour. Conserv. Recycl.* **2021**, *168*, 105439. [CrossRef]
6. ABEEólica. Infowind #30. Associação Brasileira de Energia Eólica e Novas Tecnologias. 2023, pp. 1–2. Available online: https://abeeolica.org.br/energia-eolica/dados-abeeolica/ (accessed on 14 April 2023).
7. Topham, E.; McMillan, D. Sustainable decommissioning of an offshore wind farm. *Renew. Energy* **2017**, *102*, 470–480. [CrossRef]
8. Ozoemena, M.; Cheung, W.M.; Hasan, R. Comparative LCA of technology improvement opportunities for a 1.5-MW wind turbine in the context of an onshore wind farm. *Clean Technol. Environ. Policy* **2018**, *20*, 173–190. [CrossRef]
9. Wang, L.; Wang, Y.; Du, H.; Zuo, J.; Li, R.Y.M.; Zhou, Z.; Bi, F.; Garvlehn, M.P. A comparative life-cycle assessment of hydro-, nuclear and wind power: A China study. *Appl. Energy* **2019**, *249*, 37–45. [CrossRef]
10. Brasil. Lei n° 14.182 de 12 de julho de 2021. Presidência da República do Brasil. Brasília, Brasil. 2021; pp. 1–14. Available online: https://www.planalto.gov.br/ccivil_03/_ato2019-2022/2021/Lei/L14182.htm (accessed on 2 August 2021).
11. Agência Nacional de Energia Elétrica. Sistema de Informações de Geração da ANEEL-SIGA. ANEEL. 2022. Available online: https://dadosabertos.aneel.gov.br/dataset/siga-sistema-de-informacoes-de-geracao-da-aneel (accessed on 17 August 2023).
12. Al Hamed, H. *Onshore Wind Farm Repowering Alternative Scenarios and Cost Assessment*; Uppsala University: Uppsala, Sweden, 2021; Available online: http://oatd.org/oatd/record?record=oai%5C%3ADiVA.org%5C%3Auu-435161 (accessed on 19 December 2022).
13. Ortegon, K.; Nies, L.F.; Sutherland, J.W. Preparing for end of service life of wind turbines. *J. Clean. Prod.* **2013**, *39*, 191–199. [CrossRef]
14. Knutson, K. Wind Farm Repowering and Decommissioning Is Big Business. Energy Central. 2019. Available online: https://energycentral.com/c/cp/wind-farm-repowering-and-decommissioning-big-business (accessed on 17 August 2023).
15. Hall, R.; João, E.; Knapp, C.W. Environmental impacts of decommissioning: Onshore versus offshore wind farms. *Environ. Impact Assess Rev.* **2020**, *83*, 106404. [CrossRef]
16. Coriolis Energy. The Wind Farm Life Cycle. Coriolis Energy. 2020, pp. 1–3. Available online: http://www.coriolis-energy.com/landowners/wind_farm_life_cycle.html (accessed on 3 November 2021).
17. Judge, F.; McAuliffe, F.D.; Sperstad, I.B.; Chester, R.; Flannery, B.; Lynch, K.; Murphy, J. A lifecycle financial analysis model for offshore wind farms. *Renew. Sustain. Energy Rev.* **2019**, *103*, 370–383. [CrossRef]
18. Shafiee, M.; Brennan, F.; Espinosa, I.A. A parametric whole life cost model for offshore wind farms. *Int. J. Life Cycle Assess.* **2016**, *21*, 961–975. [CrossRef]
19. Andersen, N. *Wind Turbine End-of-Life: Characterisation of Waste Material*; University of Gavle: Gävle, Sweden, 2015; Available online: https://www.diva-portal.org/smash/get/diva2:873368/FULLTEXT01.pdf (accessed on 17 January 2023).
20. Lacal-Arántegui, R.; Uihlein, A.; Yusta, J.M. Technology effects in repowering wind turbines. *Wind Energy* **2020**, *23*, 660–675. [CrossRef]
21. Topham, E.; McMillan, D.; Bradley, S.; Hart, E. Recycling offshore wind farms at decommissioning stage. *Energy Policy* **2019**, *129*, 698–709. [CrossRef]
22. Jadali, A.; Ioannou, A.; Kolios, A. A multi-attribute review toward effective planning of end-of-life strategies for offshore wind farms. *Energy Sources Part B Econ. Plan. Policy* **2021**, *16*, 584–602. [CrossRef]
23. Abadie, L.M.; Goicoechea, N. Old Wind Farm Life Extension vs. Full Repowering: A Review of Economic Issues and a Stochastic Application for Spain. *Energies* **2021**, *14*, 3678. [CrossRef]
24. Velasco, A.M.Z. *Avaliação de Investimentos em Retrofit de Parques Eólicos por Opções Reais*; Pontífica Universidade Católica do Rio de Janeiro: Rio de Janeiro, Brazil, 2017; Available online: https://www.maxwell.vrac.puc-rio.br/30877/30877.PDF (accessed on 7 January 2023).
25. Bezbradica, M.; Kerkvliet, H.; Borbolla, I.M.; Lehtimaki, P. Introducing multi-criteria decision analysis for wind farm repowering: A case study on Gotland. In Proceedings of the 1st International Conference Multidisciplinary Engineering Design Optimization MEDO 2016, Belgrade, Serbia, 14–16 September 2016; pp. 1–8. Available online: https://researchportal.tuni.fi/en/publications/introducing-multi-criteria-decision-analysis-for-wind-farm-repowe (accessed on 18 August 2023).
26. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *Int. J. Surg.* **2021**, *88*, 105906. [CrossRef]
27. Regona, M.; Yigitcanlar, T.; Xia, B.; Li, R.Y.M. Opportunities and Adoption Challenges of AI in the Construction Industry: A PRISMA Review. *J. Open Innov. Technol. Mark. Complex.* **2022**, *8*, 45. [CrossRef]

28. Yigitcanlar, T.; Kamruzzaman, M.; Foth, M.; Sabatini-Marques, J.; da Costa, E.; Ioppolo, G. Can cities become smart without being sustainable? A systematic review of the literature. *Sustain. Cities Soc.* **2019**, *45*, 348–365. [CrossRef]
29. Martinez, E.; Sanz, F.; Pellegrini, S.; Jimenez, E.; Blanco, J. Life-cycle assessment of a 2-MW rated power wind turbine: CML method. *Int. J. Life Cycle Assess.* **2009**, *14*, 52–63. [CrossRef]
30. Martinez, E.; Jimenez, E.; Blanco, J.; Sanz, F. LCA sensitivity analysis of a multi-megawatt wind turbine. *Appl. Energy* **2010**, *87*, 2293–2303. [CrossRef]
31. Min, K.J.; Lou, C.; Wang, C.H. An Exit and Entry Study of Renewable Power Producers: A Real Options Approach. *Eng. Econ.* **2012**, *57*, 55–75. [CrossRef]
32. Cherrington, R.; Goodship, V.; Meredith, J.; Wood, B.M.; Coles, S.R.; Vuillaume, A.; Feito-Boirac, A.; Spee, F.; Kirwan, K. Producer responsibility: Defining the incentive for recycling composite wind turbine blades in Europe. *Energy Policy* **2012**, *47*, 13–21. [CrossRef]
33. Zhang, D.; Liu, P.; Ma, L.; Li, Z.; Ni, W. A multi-period modelling and optimization approach to the planning of China's power sector with consideration of carbon dioxide mitigation. *Comput. Chem. Eng.* **2012**, *37*, 227–247. [CrossRef]
34. Gervásio, H.; Rebelo, C.; Moura, A.; Veljkovic, M.; Simões da Silva, L. Comparative life cycle assessment of tubular wind towers and foundations—Part 2: Life cycle analysis. *Eng. Struct.* **2014**, *74*, 292–299. [CrossRef]
35. Prabu, T.; Kottayil, S.K. Repowering a Windfarm—A Techno-Economic Approach. *Wind. Eng.* **2015**, *39*, 385–397. [CrossRef]
36. Liu, P.; Barlow, C.Y. Wind turbine blade waste in 2050. *Waste Manag.* **2017**, *62*, 229–240. [CrossRef] [PubMed]
37. Sakellariou, N. Current and potential decommissioning scenarios for end-of-life composite wind blades. *Energy Syst.* **2017**, *9*, 981–1023. [CrossRef]
38. Martínez, E.; Latorre-Biel, J.I.; Jiménez, E.; Sanz, F.; Blanco, J. Life cycle assessment of a wind farm repowering process. *Renew. Sustain. Energy Rev.* **2018**, *93*, 260–271. [CrossRef]
39. Karoui, R.; Bacha, F.; Hasni, A.; Khadraoui, H. Analysis of the Repowering Wind Farm of Sidi-Daoud in Tunisia. *IEEE Trans. Ind. Appl.* **2019**, *55*, 3011–3023. [CrossRef]
40. Teffera, B.; Assefa, B.; Bjorklund, A.; Assefa, G. Life cycle assessment of wind farms in Ethiopia. *Int. J. Life Cycle Assess.* **2021**, *26*, 76–96. [CrossRef]
41. Kitzing, L.; Jensen, M.K.; Telsnig, T.; Lantz, E. Multifaceted drivers for onshore wind energy repowering and their implications for energy transition. *Nat. Energy* **2020**, *5*, 1012–1021. [CrossRef]
42. Pryor, S.C.; Barthelmie, R.J.; Shepherd, T.J. 20% of US electricity from wind will have limited impacts on system efficiency and regional climate. *Sci. Rep.* **2020**, *10*, 541. [CrossRef]
43. Syed, A.H.; Javed, A.; Asim Feroz, R.M.; Calhoun, R. Partial repowering analysis of a wind farm by turbine hub height variation to mitigate neighboring wind farm wake interference using mesoscale simulations. *Appl. Energy* **2020**, *268*, 115050. [CrossRef]
44. Kadhirvel, B.; Ramaswamy, S.; Kirubaharan, V.; Bastin, J.; ShobanaDevi, A.; Kanagavel, P.; Balaraman, K. Optimization of the wind farm layout by repowering the old wind farm and integrating solar power plants: A case study. *Int. J. Renew. Energy Res.* **2020**, *10*, 1287–1301.
45. Bona, J.C.; Ferreira, J.C.E.; Ordoñez Duran, J.F. Analysis of scenarios for repowering wind farms in Brazil. *Renew. Sustain. Energy Rev.* **2021**, *135*, 110197. [CrossRef]
46. Rajaram, H.R.; Krishnan, B.; Guru, B. Leveraging on repowering of wind sites for potential wind-solar hybrid capacities: A case study. *Int. Energy J.* **2021**, *21*, 183–192.
47. Khan, M.A.; Javed, A.; Shakir, S.; Syed, A.H. Optimization of a wind farm by coupled actuator disk and mesoscale models to mitigate neighboring wind farm wake interference from repowering perspective. *Appl. Energy* **2021**, *298*, 117229. [CrossRef]
48. Volk, R.; Stallkamp, C.; Herbst, M.; Schultmann, F. Regional rotor blade waste quantification in Germany until 2040. *Resour. Conserv. Recycl.* **2021**, *172*, 105667. [CrossRef]
49. Grau, L.; Jung, C.; Schindler, D. Sounding out the repowering potential of wind energy—A scenario-based assessment from Germany. *J. Clean.Prod.* **2021**, *293*, 126094. [CrossRef]
50. Jezierski, A.; Mańkowski, C.; Śpiewak, R. Energy savings analysis in logistics of a wind farm repowering process: A case study. *Energies* **2021**, *14*, 5452. [CrossRef]
51. Leite, G.D.N.P.; Weschenfelder, F.; Farias, J.G.D.; Kamal Ahmad, M. Economic and sensitivity analysis on wind farm end-of-life strategies. *Renew. Sustain. Energy Rev.* **2022**, *160*, 112273. [CrossRef]
52. Simón-Martín, M.; Ciria-Garcés, T.; Rosales-Asensio, E.; González-Martínez, A. Multi-dimensional barrier identification for wind farm repowering in Spain through an expert judgment approach. *Renew. Sustain. Energy Rev.* **2022**, *161*, 112387. [CrossRef]
53. Global Wind Energy Council. *Global Wind Statistics 2017*; GWEC: Brussels, Belgium, 2018.
54. Barros, M.V.; Salvador, R.; Piekarski, C.M.; de Francisco, A.C.; Freire, F.M.C.S. Life cycle assessment of electricity generation: A review of the characteristics of existing literature. *Int. J. Life Cycle Assess.* **2020**, *25*, 36–54. [CrossRef]
55. Global Wind Energy Council. *Global Wind Report 2023*; Global Wind Energy Council: Brussels, Belgium, 2023; Available online: https://gwec.net/globalwindreport2023/ (accessed on 5 May 2023).
56. Chaurasiya, P.K.; Warudkar, V.; Ahmed, S. Wind energy development and policy in India: A review. *Energy Strateg. Rev.* **2019**, *24*, 342–357. [CrossRef]

57. Welstead, J.; Hirst, R.; Keogh, D.; Robb, G.; Bainsfair, R. SNH Commissioned Report 591: Research and Guidance on Restoration and Decommissioning of Onshore Wind Farms. 2013. Available online: https://www.researchgate.net/profile/Jean-Welstead/publication/268214857_Scottish_Natural_Heritage_Research_and_guidance_on_the_restoration_and_decommissioning_of_onshore_wind_farms/links/5464da900cf2a8cf007c0484/Scottish-Natural-Heritage-Research-and-guidance-on-the-restoration-and-decommissioning-of-onshore-wind-farms.pdf (accessed on 2 March 2023).
58. Jung, C.; Schindler, D.; Grau, L. Achieving Germany's wind energy expansion target with an improved wind turbine siting approach. *Energy Convers. Manag.* **2018**, *173*, 383–398. [CrossRef]
59. Nivedh, B.; Devi, R.; Sreevalsan, E. Repowering of Wind Farms—A Case Study. *Wind. Eng.* **2013**, *37*, 137–150. [CrossRef]
60. Villena-Ruiz, R.; Ramirez, F.J.; Honrubia-Escribano, A.; Gómez-Lázaro, E. A techno-economic analysis of a real wind farm repowering experience: The Malpica case. *Energy Convers. Manag.* **2018**, *172*, 182–199. [CrossRef]
61. Ministério de Minas e Energia. Plano Nacional de Eficiência Energética: Premissas e Diretrizes Básicas. Ministério de Minas e Energia Brasil. 2011; p. 156. Available online: www.mme.gov.br (accessed on 8 April 2023).
62. De Mesquita, J.C.M. *Estudo Sobre a Transição Energética na Matriz Elétrica Brasileira*; Universidade Federal do Ceará: Fortaleza, Brazil, 2022.
63. De Lucena Stuckert, G.F. As políticas públicas e o papel das agências reguladoras. *Rev. Direito. Sociais Políticas Públicas.* **2015**, *1*, 289–317. [CrossRef]
64. Pronińska, K.; Księżopolski, K. Baltic Offshore Wind Energy Development—Poland's Public Policy Tools Analysis and the Geostrategic Implications. *Energies* **2021**, *14*, 4883. [CrossRef]
65. Morea, D.; Bittucci, L.; Cafaro, A.; Mango, F.; Murè, P. Can the Current State Support Mechanisms Help the Growth of Renewable Energies in Wind Markets? *Sustainability* **2021**, *13*, 12094. [CrossRef]
66. Irfan, M.; Zhao, Z.Y.; Ahmad, M.; Mukeshimana, M.C. Critical factors influencing wind power industry: A diamond model based study of India. *Energy Rep.* **2019**, *5*, 1222–1235. [CrossRef]
67. Martinez, A.; Iglesias, G. Multi-parameter analysis and mapping of the levelised cost of energy from floating offshore wind in the Mediterranean Sea. *Energy Convers. Manag.* **2021**, *243*, 114416. [CrossRef]
68. Wind Europe. Decommissioning of Onshore Wind Turbines: Industry Guidance Document. Wind Eur. 2020, pp. 1–53. Available online: https://windeurope.org/data-and-analysis/product/decommissioning-of-onshore-wind-turbines/ (accessed on 8 April 2023).
69. Sarder, M.D. *Logistics Transportation Systems*, 1st ed.; Elsevier: Amsterdam, The Netherlands, 2020.
70. Han, J.; Mol, A.P.J.; Lu, Y.; Zhang, L. Onshore wind power development in China: Challenges behind a successful story. *Energy Policy* **2009**, *37*, 2941–2951. [CrossRef]
71. Serrano-González, J.; Lacal-Arántegui, R. Technological evolution of onshore wind turbines—A market-based analysis. *Wind Energy* **2016**, *19*, 2171–2187. [CrossRef]
72. Lacerda, L.S.; Junior, P.R.; Peruchi, R.S.; Chicco, G.; Rocha, L.C.S.; Aquila, G.; Junior, L.M.C. Microgeneration of Wind Energy for Micro and Small Businesses: Application of ANN in Sensitivity Analysis for Stochastic Economic Feasibility. *IEEE Access* **2020**, *8*, 73931–73946. [CrossRef]
73. Corrêa Da Silva, R.; De Marchi Neto, I.; Silva Seifert, S. Electricity supply security and the future role of renewable energy sources in Brazil. *Renew. Sustain. Energy Rev.* **2016**, *59*, 328–341. [CrossRef]
74. Castro-Santos, L.; Diaz-Casas, V. *Economic Feasibility of Floating Offshore Wind Farms*; Springer: Berlin/Heidelberg, Germany, 2016; p. 204.
75. Kazem, H.A.; Albadi, M.H.; Al-Waeli, A.H.A.; Al-Busaidi, A.H.; Chaichan, M.T. Techno-economic feasibility analysis of 1MW photovoltaic grid connected system in Oman. *Case Stud. Therm. Eng.* **2017**, *10*, 131–141. [CrossRef]
76. Poulsen, T.; Hasager, C.B. How expensive is expensive enough? Opportunities for cost reductions in offshore wind energy logistics. *Energies* **2016**, *9*, 437. [CrossRef]
77. Irish Wind Energy Association—IWEA. *Life-Cycle of an Onshore Wind Farm*; IWEA: Dublin, Ireland, 2019; Available online: https://windenergyireland.com/images/files/iwea-onshore-wind-farm-report.pdf (accessed on 11 September 2023).
78. dos Santos, M.A.T. *Sistema de Medição de Desempenho para Operação e Manutenção de Parques Eólicos no Brasil*; Universidade Federal do Rio Grande do Norte: Natal, Brazil, 2016.
79. Castro-Santos, L.; Vizoso, A.F.; Camacho, E.M.; Piegiari, L. Costs and feasibility of repowering wind farms. *Energy Sources Part B Econ. Plan. Policy* **2016**, *11*, 974–981. [CrossRef]
80. Varella Filho, H.C. *Medição de Desempenho na Cadeia de Suprimentos da Energia Eólica: Proposta de um Conjunto de Indicadores de Desempenho*; Universidade Federal do Rio Grande do Norte: Natal, Brazil, 2013.
81. Draycott, S.; Szadkowska, I.; Silva, M.; Ingram, D.M. Assessing the macro-economic benefit of installing a farm of oscillating water columns in Scotland and Portugal. *Energies* **2018**, *11*, 2824. [CrossRef]
82. Colmenar-Santos, A.; Campíñez-Romero, S.; Pérez-Molina, C.; Mur-Pérez, F. Repowering: An actual possibility for wind energy in Spain in a new scenario without feed-in-tariffs. *Renew. Sustain. Energy Rev.* **2015**, *41*, 319–337. [CrossRef]
83. de Melo, D.C. *Framework de um Sistema Especialista de Análise Econômica para Empreendimentos de Usinas Eólicas Offshore*; UFRN: Natal, Brazil, 2020.
84. Kaiser, M.J.; Snyder, B. *Offshore Wind Energy Installation and Decommissioning Cost Estimation in the U.S. Outer Continental Shelf*; National Technical Reports Library: Herndon, VA, USA, 2011; p. 340.
85. Bose, A.; Dürr, T.; Klenke, R.A.; Henle, K. Collision sensitive niche profile of the worst affected bird-groups at wind turbine structures in the Federal State of Brandenburg, Germany. *Sci. Rep.* **2018**, *8*, 3777. [CrossRef] [PubMed]

86. Piasecka, I.; Tomporowski, A.; Flizikowski, J.; Kruszelnicka, W.; Kasner, R.; Mroziński, A. Life cycle analysis of ecological impacts of an offshore and a land-basedwind power plant. *Appl. Sci.* **2019**, *9*, 231. [CrossRef]
87. Bonou, A.; Laurent, A.; Olsen, S.I. Life cycle assessment of onshore and offshore wind energy-from theory to application. *Appl. Energy* **2016**, *180*, 327–337. [CrossRef]
88. Schreiner, G.H.; Codonho, M.L.P.C.F. Descomissionamento ambiental: Análise da temática em empreendimentos de geração de energia eólica. *Rev. Direito. Ambient.* **2018**, *3*, 92. Available online: https://dspace.almg.gov.br/handle/11037/30738 (accessed on 18 September 2023).
89. Tereza, J.C. Levantamento de Opinião Sobre o Descomissionamento de Parques Eólicos no Brasil. Universidade Federal de Santa Catarina: Florianópolis, Brazil, 2019; Available online: https://repositorio.ufsc.br/bitstream/handle/123456789/203255/TCCEngenhariadeEnergia-JaymaraChagasTereza.pdf?sequence=1&isAllowed=y (accessed on 21 August 2023).
90. Nie, Y.; Zhang, G. Indicator system to evaluate the effectiveness and efficiency of China clean power systems. *Mitig. Adapt. Strateg. Glob. Chang.* **2020**, *25*, 1381–1401. [CrossRef]
91. Eising, M.; Hobbie, H.; Möst, D. Future wind and solar power market values in Germany—Evidence of spatial and technological dependencies? *Energy Econ.* **2020**, *86*, 104638. [CrossRef]